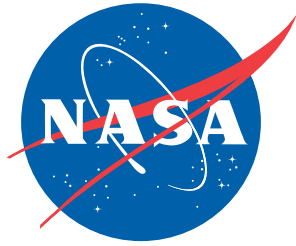


NASA/TM-2010-216868/Volume II  
NESC-RP-08-00487



# Constellation Program (CxP) Crew Exploration Vehicle (CEV) Parachute Assembly System (CPAS) Independent Design Reliability Assessment

## *Appendices*

*Michael J. Kelly/NESC  
Langley Research Center, Hampton, Virginia*

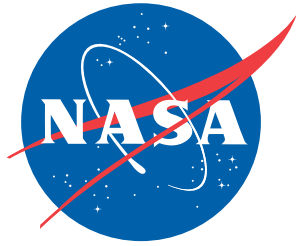
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NASA/TM-2010-216868/Volume II  
NESC-RP-08-00487



# Constellation Program (CxP) Crew Exploration Vehicle (CEV) Parachute Assembly System (CPAS) Independent Design Reliability Assessment

## *Appendices*

*Michael J. Kelly/NESC  
Langley Research Center, Hampton, Virginia*

National Aeronautics and  
Space Administration

Langley Research Center  
Hampton, Virginia 23681-2199


November 2010

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**Constellation Program (CxP)  
Crew Exploration Vehicle (CEV)  
Parachute Assembly System (CPAS)  
Independent Design Reliability Assessment**

**NRB Review Date: August 26, 2010**

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## Appendix A. Stakeholder Request (November 2008)

National Aeronautics and Space Administration  <b>Lyndon B. Johnson Space Center</b> 2101 NASA Parkway Houston, Texas 77058-3696							
October 21, 2008							
Reply to Attn of: EA-08-030							
<table border="0"> <tr> <td style="vertical-align: top;">TO:</td> <td>LaRC-C1/Director, NASA Engineering and Safety Center (NESC)</td> </tr> <tr> <td style="vertical-align: top;">FROM:</td> <td>EA/Director, Engineering</td> </tr> <tr> <td style="vertical-align: top;">SUBJECT:</td> <td>Request for CEV Parachute Assembly System (CPAS) Reliability Analysis</td> </tr> </table>		TO:	LaRC-C1/Director, NASA Engineering and Safety Center (NESC)	FROM:	EA/Director, Engineering	SUBJECT:	Request for CEV Parachute Assembly System (CPAS) Reliability Analysis
TO:	LaRC-C1/Director, NASA Engineering and Safety Center (NESC)						
FROM:	EA/Director, Engineering						
SUBJECT:	Request for CEV Parachute Assembly System (CPAS) Reliability Analysis						
<p>In support of the Constellation Program, JSC Engineering is responsible for developing and delivering the CPAS as Government-furnished equipment. To date, the Orion Safety, Reliability and Quality Assurance Team has generated CPAS reliability estimates based on historical data from other parachute systems such as the Shuttle solid rocket booster recovery system. The Orion Engineering Review Board held September 29-30, 2008, which addressed the preliminary design status of all CEV systems, identified CPAS as the principal driver for overall Orion reliability based on this estimate. The CPAS project is reviewing and modifying this estimate to incorporate our internal parachute expertise.</p>							
<p>Given the criticality of the CPAS, I request the NESC to review the reliability analysis of the CPAS in the context of the existing design and planned development program and to make recommendations for improving either if appropriate. Of particular interest is the planned development test program due to its value in uncovering design flaws contrasted with the cost and resources required. Striking the proper balance between reliability enhancing tests and total project cost and schedule is important for the success of the Program.</p>							
<p>The ability of your organization to engage both internal NASA and external military and industry expertise and knowledge for this activity would be invaluable. This comprehensive analysis could identify design and/or process improvement opportunities to increase the overall reliability of the CPAS, as well as to ensure success of the integrated system.</p>							
<p>Please contact me directly for any questions at (281) 483-1396, or at my e-mail address <a href="mailto:stephen.j.altemus@nasa.gov">stephen.j.altemus@nasa.gov</a>.</p>							
Stephen J. Altemus							

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## Appendix B.1. Stakeholder Outbrief of Interim Recommendations 1 (April 2009)

The attached version of Stakeholder Outbrief 1 differs slightly from that which was approved by the NRB. Figures included to facilitate board member understanding were removed in the stakeholder package.

<b>NESC Review Board</b>	Mike Kelly
	April 16, 2009

### Crew Exploration Vehicle (CEV) Parachute Assembly System (CPAS) Independent Reliability Assessment


#### Stakeholder Outbrief of Interim Recommendations

Project Assessment between December 2008 and March 2009

**Mike Kelly**

NESC Principal Engineers Office

**April 21, 2009**

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<b>NASA Engineering &amp; Safety Center</b>	Mike Kelly
	April 16, 2009

In 2003, the Columbia Accident Investigation Board (CAIB) observed that NASA's safety organization lacked adequate technical expertise and resources for independent technical reviews of NASA's Programs and Projects.

The NASA Engineering & Safety Center (NESC) was formed as a response to this observation, with a mission to provide the Agency's Programs and Projects with rigorous independent technical perspectives on their most critical technical issues.

NESC is independent:

- Centrally managed and funded through the Office of Chief Engineer.
- Unaffiliated with the Programs our teams evaluate.
- Unbiased by any specific NASA Center.
- Has an independent engineering chain of command to assure an avenue for consideration of all points of view.


NESC teams are broad-based:

- Experts from all ten NASA Centers and HQ
- About one-quarter of NESC team members are from outside the Agency
  - Industry
  - Academia
  - Other U.S. Government Agencies & National Labs

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<b>NASA Engineering &amp; Safety Center</b>	Mike Kelly
	April 16, 2009


NESC teams engage in a variety of activities:

- Conduct technical assessments of high risk issues by reviewing data and/or performing independent testing and analysis to create new data, creating data-driven findings and observations, and generating solution-driven, preventative or corrective recommendations that are rigorously grounded in team findings and observations.
- Engage in forward-looking technical investigations, which may include performing independent tests and analyses with high potential to advance knowledge within a discipline.
- Perform design development and demonstration work, which may include conducting design trade studies, performing preliminary design definition, weights trades, structural analyses, systems analyses, detailed design work, design integration work, and constructing full-scale test articles for laboratory and flight testing.

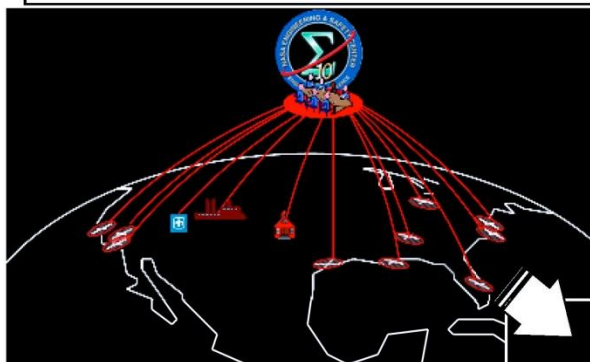
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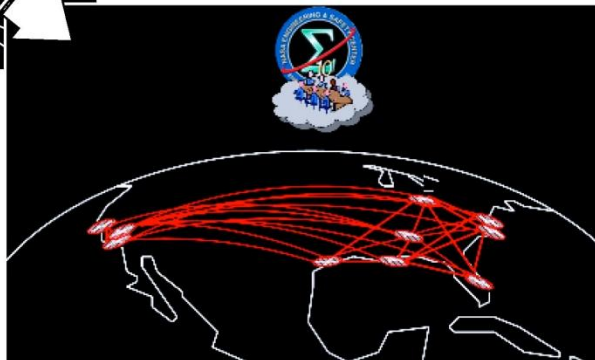
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<b>NASA Engineering &amp; Safety Center</b>	Mike Kelly
	April 16, 2009



NESC teams are broad-based.


NESC teams persist virtually as networks of technical expertise, even after assessments are completed, becoming an enduring asset for NASA Programs and Projects.



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<h1 style="text-align: center;">Agenda</h1>	Mike Kelly
	April 16, 2009


- Background
- Team Listing
- Recommendations



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<h1>Background</h1>	Mike Kelly
	April 16, 2009

- The NESC independent CPAS reliability assessment team was chartered to assess the project's preliminary design, its preliminary estimates for reliability, and its preliminary developmental test program.
  - The stakeholder requested a “comprehensive analysis (that) could identify design and/or process improvement opportunities to increase overall reliability of the CPAS, as well as ensure success of the integrated system.”
  - Complete stakeholder request is in backup charts.
- The team is comprised of parachute system design and test experts, statistics and reliability analysis and test experts, and select discipline experts.
- A final report of Findings, Observations and Recommendations is planned for August 2009.

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<h1>Background</h1>	Mike Kelly
	April 16, 2009

- The “period of initial review” was from December 2008 through March 2009.
- During this three-month period:
  - The CPAS Subsystem team was clearly working very hard and with determination to establish an architecture and a set of requirements that would result in a robust and reliable design, given a very complex design problem with many competing parameters.
  - Design details and requirements evolved significantly and rapidly.
  - PDR was delayed from June 2009 to (est) August or September 2009.
- The NESC team reviewed material from CPAS teleconferences and other material that was provided directly by the project upon request.
  - Documents and presentations reviewed by the team are listed in Backup charts.

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<h1>Background</h1>	Mike Kelly
	April 16, 2009

- The NESC team discussed the various design architectures under consideration. The team also discussed the available reliability estimates and methods employed.
- CPAS had not established development test plans or a verification and validation matrix to a sufficient degree to provide to the NESC team for review.
  - Since test plan review was a key team objective, the team revised its schedule of assessment tasks to accommodate (Change approved by the NESC Review Board on 3-26-09).
  - The NESC team plans to remain engaged with the Project at a reduced rate between April and June 2009, and increase its engagement during June 2009, or whenever a stable design architecture is in place, and preliminary development test plans are available for assessment.

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<h1>Background</h1>	Mike Kelly
	April 16, 2009

- Interim Recommendations are directed towards the CPAS Subsystem team, unless otherwise indicated.
- Stakeholder Outbrief of these Interim Recommendations is intended to help lower technical and schedule risk in the current pre-PDR development phase.
- There are 30 Interim Recommendations; the first 12 are considered a top priority for action as soon as practical.

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<h1>Background</h1>	Mike Kelly
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- The following acronyms apply to design architectural options that were under consideration during the period of initial review.
  - RAO = Rigidly Attached Option
  - LAO = Loosely Attached Option
  - PDO = Pilot Deployed Option (Loosely Attached Pilots)
  - 3PA = Harnessed Mains
  - SPA = Single Point Attach Mains

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<h1>Team Listing</h1>		Mike Kelly  April 16, 2009
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Last Name	First Name	Discipline	Organization/Location	Email Address
Kelly	Michael	Team Lead	NASA, LaRC	michael.j.kelly-1@nasa.gov
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Herr	Michael	Parachute Systems	Naval Air Warfare Center Weapons Division (NAWCWD), China Lake	michael.herr@navy.mil
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Won	Gary	Electrical	ATK, GSFC	gary.k.won@nasa.gov
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Johnson	Ken	Reliability (NEST)	NASA, GRC	kenneth.g.johnson@nasa.gov
Lee	Wayne	Parachute Systems	NASA, JPL	wayne.j.lee@jpl.nasa.gov
<b>Support</b>				
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Johnson	Loutricia	MTSO Program Analyst	NASA, LaRC	loutricia.s.johnson@nasa.gov
Snare	Carolyn	Technical Writer	ATK, LaRC	carolyn.c.snare@nasa.gov

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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

Action recommended as soon as practical –

**R-1: Create a consistent, clear methodology to generate reliability estimate *uncertainties*. (O-1)**


- When reliability estimates are communicated to stakeholders, uncertainty estimates should be included, with an explanation that these uncertainties will be large for pre-PDR design architectures.

**R-2: Establish a reliability *budget*. (O-2)**

**R-3: Evaluate the use of a *volume budget* for the forward bay to manage main parachute pack volume growth before and after PDR. (F-1, F-2, O-3)**

**R-4: Orion Project should reassess if the current forward bay volume allocation is sufficient to generate a reliable CPAS design. (O-4, O-24)**



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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

**Action recommended as soon as practical –**

**R-5: Apply a *comprehensive systems approach* to the design development, analysis, and testing efforts. (O-5)**

- Address risks with priority given to those identified by the FTA to have the highest uncertainties ("risk balancing").
- Include component-level verification tests to aid in tracking requirements compliance and risk acceptance/mitigation.
- Include planned means for verification and validation of simulation models.


**\*NESC Report, DDT&E attached.**

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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009


**Action recommended as soon as practical –**

**R-6: Use *verified and validated* analysis codes to generate reliability estimates. (F-3, O-6)**

- Review the techniques and assumptions analysts made when building DCLDYN analytical models, and the validity and method of derivation of the distributions from the CPAS Gen-I data or all pertinent input parameters.
- Characterize the limitations of the DCLDYN code's features, heritage, and the applicability of validation test data.
- Cross-check between analysis codes (e.g., DCLDYN and DSS) to characterize their capabilities, assumptions, and limitations.

**R-7: Adopt a single, configuration-controlled document for distributing CPAS simulation parameters to other Orion Project Analysis Teams. (F-4)**

- With appropriate traceability.
- Maintained in a common location
- System definitions and data should be kept in data formats that are easily updated and read

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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

**Action recommended as soon as practical –**

**R-8: S&MA and Design team members should *more actively integrate* their tasks and activities. (F-5, O-7)**

- Possible methods to increase coordination could include conducting more frequent and focused teleconferences, increasing the use of electronic networking tools, and/or periodic co-location between members from both teams.


**R-9: Assess the merits of assigning a Systems Engineer as a “Phase Lead” with a dedicated responsibility for oversight of interfaces and integration with other subsystems. (F-6, O-8)**

- Consider the following possible roles and relationships for the Phase Lead:
  - Report to the SE&I Team Chair.
  - Be assigned an “ownership” of aspects of CPAS that cross interfaces.
  - Have regular interaction with other subsystems organizations and management, with freedom to move across subsystem, system and project office boundaries to ensure overall EDL success.
  - Be empowered to assess the effects of proposed CPAS design changes on other subsystems that interface with CPAS, and vice versa, and to negotiate changes with other subsystems.

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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

**Action recommended as soon as practical –**

**R-10: Conduct comprehensive ground tests to assess the risk of damage to drogue and main parachute components from *Near-Field contact* with CM and FBC structure. (F-7, O-9)**

- Require a mockup with representative geometric details of the CM including all protrusions on the OML and in the forward bay.
- Address risks to parachute components from:
  - D-bag contact with CM and FBC structure during extraction from stowage.
  - Direct contact with CM and FBC structure.
  - Rapid extraction from a d-bag due to d-bag extraction hindrance.
  - Direct contact with potentially sharp edges of separation surfaces including LAS Wells, drogue mortar tubes, and the LIDS Ring.
- Pre-test planning for contact tests should include:
  - Assessment of risks from relative motion between parachute components and structure along any combination of three axes: drag across, slide along or strike against.
  - Assessment of risks of any contact with CM surfaces that may be residually hot after reentry.

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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

Action recommended as soon as practical –

**R-11: Assess the risk quantitatively, that components from more than one main parachute could be damaged by *Far-Field contact* with the FBC. (O-10)**

**R-12: Establish a *comprehensive process* for testing and evaluating the parachute structural joint efficiencies. (O-11)**

- The process should include fabrication of sample joints, environmental conditioning, and structural testing.

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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

Additional recommendations –


**R-13: Discontinue use of SRB data to generate estimates for the probability of Near-Field contact of main parachute components with the CM and FBC structure. (F-8)**

**R-14: Utilize applicable data from the geometrically similar Apollo Program ELS to generate estimates for the probability of Near-Field contact of main parachute components with the CM and FBC structure. (F-9)**

- When Apollo Program ELS data is not available, conduct original analyses and tests to generate data for reliability estimates for Near-Field contact.

**R-15: Maintain *only one* fault tree for CPAS FTA. (F-10)**

**R-16: Review the sufficiency, applicability, and limitations of reliability estimates that were generated using the load/material property distribution-intersection method and assess from this review whether additional material testing is indicated. (F-11, O-12)**


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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

**Additional recommendations –**

**R-17: Consider the following PTRS modifications. (F-12)**

- Specify a complete set of initial conditions for drogue mortar firing.
- Specify limits to the parachute peak load directions.
- Directed requirement revisions:
  - [I.CPAS.CM.006] in a statistically verifiable form.
  - [I.CPAS.CM.011] to include the nominal condition.
  - [R.CPAS.012] to include the assumed status (i.e., operational, non-operational, or both cases must be considered) of the parachute that had a skipped reefed stage.
  - [R.CPAS.012] in terms of percentiles.

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<h1>Recommendations</h1>	Mike Kelly
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Additional recommendations –


**R-18: Select a pack shape that is as geometrically simple as possible. (F-13)**  
• Minimize geometric features that result in packing into sloping surfaces.

**R-19: Assess using a *uniform retention and simple release* system conceptually similar to the Apollo ELS Block II design. (F-14)**

**R-20: Develop pack inspection methods *integrally* with packing procedures, and retain procedure developers as packers and inspectors for operational vehicles. (F-15, F-16)**

**R-21: Characterize the effectiveness of X-Ray NDI with representative pack shapes and packing densities. (F-17, O-13, O-3)**



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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

Additional recommendations –

**R-22: Investigate alternative/complementary NDI methods to assure reefing system integrity after packing. (O-14)**


**R-23: Assess if fabric curtains or foam materials could prevent damage to CPAS main parachute components during deployment. (RAO only) (F-18, O-15)**

**R-24: Search applicable lessons learned databases for packing procedures that can mitigate reliability risks. (O-16)**

**R-25: Assess the risks quantitatively of a single instance of TPS damage causing damage to a drogue harness leg from each drogue harness. (O-17)**

- Consider redundant drogue harness leg TPS protection such as aluminized fiberglass sleeves.



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<h1>Recommendations</h1>	Mike Kelly
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Additional recommendations –

**R-26:** Include redundant and independently engaged kicker straps for each main d-bag, if kicker straps become baseline. (O-18, O-19)

**R-27:** *Quantitatively* assess the probability of main parachute entanglement during deployment, for abort and reentry. (RAO, LAO, PDO) (F-19)

**R-28:** Assess by analysis and test the damage tolerance and residual strength of Kevlar® risers and suspension lines and canopy structural components with different types of damage that may be inflicted by *Far-Field* FBC contact. (O-10)

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<h1>Recommendations</h1>	Mike Kelly
	April 16, 2009

**Additional recommendations –**

**R-29: Consider the following specific tests for inclusion in the comprehensive test plan. Candidate tests are organized by rigging, ground, air, and lab tests. (F-20, O-20)**  
**[List of tests and objectives is in Backup charts]**


**R-30: Critically reassess if a failed main parachute is an independent event following a failed drogue parachute. (O-21, O-22)**

- Assessment results are needed to support the CPAS decision to change the pad abort failure tolerance requirement from 'one failed drogue and one failed main,' to 'one failed drogue or one failed main.'

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<h1>Lesson Learned</h1>	Mike Kelly
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**LL-1: NASA Programs and Projects should not rely on contractors reports surviving, but rather should document development efforts themselves and store them in a topic-specific or discipline-specific Agency repository (O-23).**


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<h1>Backup</h1>	Mike Kelly
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<b>Backup – List of Specific Tests Recommended for Consideration in R-29</b>	Mike Kelly
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**Rigging tests:**


- to provide data to help establish the probability of damage that can result from mis-rigging
- to demonstrate the ability, using various NDI methods, to detect mis-rigging

**Structural proof and ultimate load tests** (coordinated with Lockheed)

- FBC attach fitting for two drogue harness legs, with the most adverse loading conditions as determined by analyses, to assure that one failed attachment does not fail its mate.
- CM Gusset attach fitting for three main risers, with the most adverse loading conditions as

**Ground tests** to anchor any modeling and simulation results that are used to generate quantitative reliability estimates and to characterize the following risks:


- Characterize drogue mortar performance under adverse conditions to assure there is sufficient mortar energy to get the drogue d-bag out of the tube with sufficient velocity to get it far enough into the air stream to begin inflating.
  - Adverse conditions may include but are not limited to, adverse attitude of the Orion capsule, aged packed drogue parachute including riser, and loss of a single initiator.
  - Establish the optimal method for placement of the metallic drogue confluence ring in the drogue mortar, to minimize the risk of damage to the mortar's edge and subsequent damage to the drogue fabric.

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<b>Backup – List of Specific Tests Recommended for Consideration in R-29</b>	Mike Kelly
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Ground tests (continued):


- Characterize the risks of Near-Field contact of main d-bags with the FBC structure with kicker straps.
- Validate analyses of main d-bag rigid body motion in response to extraction forces, to characterize the risk of main d-bag contact with the tunnel during extraction.
- Characterize the performance of energy modulators at representative rates of extension. (LAO)
- Demonstrate the reliable extraction, deployment, function, and robustness of the rotation torque limiter and its components, in nominal and adverse conditions.
- Ground tests to characterize the effect on torque limiter function from one failed riser (or harness leg). (3PA, SPA)
- Validate analyses of the effect peak local stresses on risers (or harness legs) from maximum expected number of twists, plus a margin. (3PA, SPA)
- Demonstrate the reliable extraction of the contents from any stowage container, under adverse conditions, without damage to the contents or liberation of the container.
- Demonstrate the reliable extraction of the contents from all drogue, pilot and main bags, with secondary objective to characterize the risks of burn damage for Nylon®, Kevlar®, and especially Vectran® parachute components.

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<b>Backup – List of Specific Tests Recommended for Consideration in R-29</b>	Mike Kelly
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Air drop tests to anchor any modeling and simulation results that are used to generate quantitative reliability estimates and characterize the following risks:

- Verify and certify all parachute structural margins
  - Early attention to the main parachute vent hoop element, which preliminary results show has a low DF and low reliability estimate.
- Demonstrate the reliable extraction of the contents from all drogue, pilot and main d-bags.
- Drogue confluence rings impacting each other during deployment.
- Pilot parachute entanglement during deployment. (PDO)
- Main parachute entanglement during deployment. (RAO, LAO)
- Characterize parachute opening characteristics, including an assessment of cluster opening effects.
- Characterize parachute disreefing loads
  - DCLDYN Monte Carlo analyses predicted to potentially exceed design load requirements, represents high uncertainty.
- Characterize the effect of the wake from the Orion capsule on the deployment of the parachute system.
- Characterize the performance of energy modulators. (LAO)
- Demonstrate the reliable extraction, deployment, function, and robustness of the rotation torque limiter and its components, in nominal and adverse conditions.
- Deployment tests of auxiliary chutes using a representative boilerplate FBC, to verify and validate the reliability of the auxiliary chute system (opening reliability in airspeed, entanglement).

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<b>Backup – Stakeholder Request</b>	Mike Kelly
	April 16, 2009

National Aeronautics and  
 Space Administration  
 Lyndon B. Johnson Space Center  
 2101 NASA Parkway  
 Houston, Texas 77058-3686



October 21, 2008

Memorandum  
 EA-08-030

TO:            LDR/CD/Deputy, NASA Engineering and Safety Center (NESC)  
 FROM:        EA/Deputy, Engineering  
 SUBJECT:     Request for CEV Parachute Assembly System (CPAS) Reliability Analysis

In support of the Constellation Program, JSC Engineering is responsible for developing and delivering the CPAS as a proven and validated capability. To date, the Orion Safety, Reliability and Quality Assurance Team has generated CPAS reliability estimates based on historical data from other parachute systems such as the Shuttle solid rocket booster recovery system. The Orion Engineering Review Board held September 29-30, 2008, which addressed the preliminary design status of all CEV systems, identified CPAS as the principal driver for overall Orion reliability based on this estimate. The CPAS project is reviewing and modifying this estimate to incorporate our internal programmatic activities.

Given the criticality of the CPAS, I request the NESC to review the reliability analysis of the CPAS in the context of the existing design and planned development program and to make recommendations for improving either if appropriate. Of particular interest is the planned development test program due to its value in uncovering design flaws contrasted with the cost and resources required. Striking the proper balance between reliability enhancing tests and total project cost and schedule is important for the success of the program.

The ability of your organization to engage both internal NASA and external military and industry expertise and knowledge for this activity would be invaluable. This comprehensive analysis could identify design and/or process improvement opportunities to increase the overall reliability of the CPAS, as well as to ensure success of the integrated system.

Please contact me directly for any questions at (281) 483-1396, or at my e-mail address [stephen.j.lentini@nasa.gov](mailto:stephen.j.lentini@nasa.gov).


Stephen J. Lentini

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<h1>Findings &amp; Observations</h1>	Mike Kelly
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- F-1: The CPAS Subsystem's Project Technical Requirements Specification (PTRS) specifies that the "CM is required to provide volume to ensure CPAS main parachute packing density is less than or equal to 38 lbm/ft<sup>3</sup>," but the projected pack density for the main parachute is currently projected to be between 43.7 and 54.2 lbm/ft<sup>3</sup>, depending on certain design options.
- F-2: The amount of observed damage to Apollo ELS Block II parachute components increased during development in proportion to increases in pack density.


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F-3: DCLDYN mis-predicted opening load and inflation times for pilots, drogues, and mains during Gen-1 testing. DSS was used to correlate some Gen-1 test data, but Gen-1 test reports did not include direct comparisons of DSS data with DCLDYN data.

F-4: CPAS Design Team data and contemporary data from other sources are inconsistent.


- IDR charts (revised Feb 2009) and charts from the LM ERB Orion-09-0355 (Mar 12, 2009) each show the main canopies' combined drag coefficient as 0.94 for 2 chutes and 0.97 for 3 chutes, but the ODAC-3 Parachute Model Memo, CEV-LRS-08-004 Rev A (Jan 2009), pg 11, shows the main canopies' combined drag coefficient as 0.718 for 2 chutes and 0.896 for 3 chutes.
- IDR charts (revised Feb 2009) show the Drogue risers to be 65.4 ft. long, but CEV-LRS-08-004 Rev A (Jan 2009), "ODAC-3 Parachute Model Memo" pg 10, shows the riser lengths to be 48.8 ft long

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<h2>Findings &amp; Observations</h2>	Mike Kelly
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F-5: The CPAS functional organization is complex, matrixed and geographically dispersed. Contractor Jacobs ESCG has the principal Safety and Mission Assurance (S&MA) responsibilities and Airborne Systems has the principal Design Development responsibilities.

F-6: There were no references to application of NASA SP-2007-6105, NASA Systems Engineering Handbook or NPR 7123.1A, NASA Systems Engineering Processes and Requirements in the material reviewed by the NESC team.

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F-7: The CPAS design poses risk of Near-Field contact of main d-bags, Near-Field contact of main parachute components during extraction from d-bags, and Near-Field contact of main parachute components during deployment.

F-8: Solid Rocket Booster (SRB) experience data is inapplicable for generating reliability estimates of Near-Field contact of CPAS main parachute components with the CPAS Crew Module (CM) structure (RAO, LAO, PDO) or with the Forward Bay Cover (FBC) structure (LAO, PDO), because the SRB and its frustum are geometrically dissimilar to the CPAS CM and its FBC.

F-9: Apollo Earth Landing System (ELS) experience data is applicable for generating reliability estimates for Near-Field contact of CPAS main parachute components with CM structure (RAO, LAO, PDO) and FBC structure (LAO, PDO), because of the geometric similarity of the Apollo CM and its Forward Heat Shield (FHS), to the CPAS CM and its FBC.


- The Apollo data is inapplicable for Near Field contact with FBC structure for RAO.

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F-10: The CPAS S&MA Team is maintaining more than one fault tree for different purposes, creating risks of inadvertent omission or inappropriate inclusion of faults as the system rapidly evolves approaching PDR.

F-11: The CPAS Design Team (Airborne) generates reliability estimates for parachute component failures using a load/material property distribution-intersection reliability estimation method, and provides them to the CPAS S&MA Team (Jacobs) for inclusion in the CPAS Subsystem team's FTA.


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F-12: Some CPAS requirements are incomplete, unspecific, or unclear.

- [I.CPAS.CM.006] CPAS shall limit the vertical descent rate of the CM to less than 10.07 m/s (33.0 ft/s) at standard sea-level conditions (as defined in NASA-TM-X-74335, U.S. Standard Atmosphere, 1976) for a maximum CM mass of 9,464.2 kg (20,865.0 lbm).
- [I.CPAS.CM.011] CPAS shall limit the peak total parachute load (3-sigma) to less than the peak loads defined in Table 3.3-1, Parachute Peak Loads, under all fault conditions defined in [R.CPAS.018], [R.CPAS.017], and [R.CPAS.129].
- [R.CPAS.012] CPAS shall design to meet or exceed the load dispersions for each fault case defined in Table 3.3-2, Parachute Load Dispersions.




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<h2 style="margin: 0;">Findings &amp; Observations</h2>	Mike Kelly
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F-13: The irregular shape of the CPAS main deployment bags (d-bags), with concavities and acute corners, and the location of their closure flaps on their bottom, pose risks of damage to parachute components from packing into sloping or complex surfaces. Irregular shapes also necessitate complex retention schemes.

F-14: The complexity of the main d-bag's retention release system poses risks of failure of the d-bag to be extracted, premature release, or hindrance of the d-bag's extraction, all of which can result in the loss of a main parachute.


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F-15: Several sources cite rigging and packing errors as the principal source of parachute deployment failures. The Project estimates deployment failure due to rigging error for the main parachutes at 1:20,000.

F-16: The Apollo ELS packing procedures were developed during the qualification program and imposed throughout the operational program. The mitigation of reliability risks that can derive from rigging and packing errors was mitigated in part by the transfer of personnel who developed the procedures into positions of operational inspection.




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F-17: The Project makes an unqualified assessment that there is a “remote” chance of failing to detect a damaged reefing ring or prematurely triggered reefing line cutter using pre-flight X-Ray Non Destructive Inspections (NDI). The project estimates the risk of skipped reefing stage at 1:200,000.


F-18: Fabric curtains and foam materials installed inside the SRB frustum mitigate the risk of SRB main parachute components being damaged by dragging along and striking against the SRB frustum and Main Parachute Support Structure (MPSS) bipod struts during deployment.

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F-19: The CPAS S&MA Team uses an oversimplified method to estimate the risk of main parachute entanglement during deployment after FBC release, considering CM rolling, but not pitching.


- The CPAS team assigns the probability of entanglement at 1:1,000,000 based on an estimate that the CM will not roll more than 240 degrees in an estimated 3 seconds between FBC release and main parachute line stretch. (RAO, LAO)
- No distinction was made between entanglement risks following reentry and pad abort.
- No CPAS estimate was reviewed for the probability of entanglement for the pilot-deployed option. (PDO)

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F-20: Specific tests will be necessary for specific CPAS architectures in order to assure a robust, reliable design.

O-1: In September 2008, the CPAS Subsystem team communicated to Project stakeholders an estimate of overall system reliability for a pre-PDR CPAS architectural option, without communicating attendant uncertainties. Communicating reliability estimates without uncertainties can result in decision makers having insufficient understanding of reliability risks.

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- O-2: The CPAS S&MA team is not utilizing a reliability budget for its FTA. A reliability budget includes calculations of quantitative component reliability (and uncertainty), rolled up to a total system reliability (and uncertainty), with a budgeted reserve that is managed like a mass growth allowable, shrinking as the system matures.
- O-3: There is expert consensus that pack density over 40 lbm/ft<sup>3</sup> creates added reliability risks including damage to hardware items and soft materials in parachute pack assemblies. This damage can lead to parachute inflation malfunctions that cause loads to exceed design limit loads, or to components that fail at loads below design limit loads. Either of these outcomes can result in catastrophic parachute system failures. A pre-PDR design with pack density above 40 lbm/ft<sup>3</sup> cannot accommodate likely increases in pack density from design growth or vehicle growth during development, both of which occurred during Apollo development.

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- O-4: The Apollo ELS main parachutes used much of the volume of three of its four forward bay sectors (total 75%, minus the volume for pilot mortars and uprighting bags). Current CM allocation provides for 3 of 6 sectors (total 50%, minus the volume for uprighting bags) for CPAS main parachute packs. Drogue mortars and other parachute system equipment occupy proportionally equivalent percentages of total volume in the forward bays of their respective vehicles. It was not possible to ascertain what equipment in the CPAS forward bay comprises the difference.
- Components that may not be related to crew survival should not compete for forward bay volume with CPAS components, if their inclusion introduces CPAS reliability risks that may adversely affect the overall probability of LOC.

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O-5: Review of Gen 1 test reports suggests that in 2007 and 2008 there was a lack of a systematic process in establishing the basis for and the conduct of testing. The Apollo Experience Report – Earth Landing System (ELS), NASA TN D-7437, (1973), illustrates the great extent of the testing that was necessary to demonstrate the overall reliability of the ELS system, to make it suitable for manned flight. It also illustrated the need for thorough systems integration and compatibility verification. Adopting a comprehensive systems approach to design, development and testing can deliver a robust, reliable system in a cost-efficient manner.




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O-6: DCLDYN appears to be the Design Team's principal analysis tool. The Project is using its results to support critical design decisions, but its veracity and validity are not apparent. Appropriately validated parachute analysis tools will be critical to the design of CPAS and the verification of requirements.


O-7: During the period of initial review, it appeared that reliability estimation was seen as an appended task instead of a value-adding integrated discipline, although interaction appeared to be improving in March 2009.

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O-8: Event trees for any of the CPAS architectures being considered include complex networks of events that involve numerous system components that interact with each other in different ways during different events. Some CPAS components interface with other systems that are being developed by other teams in the matrixed organization. Pre-PDR system development is an iterative process that necessarily needs to involve coordination with the interfaced systems. The complexity of communicating across an extended matrixed organization can hinder thorough investigation of system component interfaces with other systems. During the period of initial review, minimal interface control information had been generated by the CPAS Subsystem team.



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- O-9: Apollo engineers assessed risks of abrasion, friction damage, hang-up objects and sharp edges and addressed each one by analysis and testing with full-scale representative mockups. The CPAS Gen-1 forward bay full-scale mockup shown in pictures in IDR charts lacks significant geometric details for such a series of tests.
  
- O-10: Using a plausible but unverified rationale that damage to Kevlar® risers and suspension lines will be minimal if impacted while lightly loaded, the CPAS Subsystem team actively discounts the risk of damage to critical components of more than one main parachute, from Far-Field contact with the FBC. Far-Field contact risk increases if auxiliary chutes do not become part of the system, or if the auxiliary chute subsystem malfunctions.

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- O-11: The CPAS configurations reviewed make use of multilayered and dissimilar materials, Nylon®, Kevlar®, and Vectran®, in joint construction. The behavior and efficiencies of such construction must be fully characterized to meet strength and mass design goals. Detailed knowledge of parachute joint efficiencies for each joint in the assembly is critical for successful recovery system design.
- O-12: Information reviewed by the NESC Team did not reveal whether material tests that generated distributions used in the load/material distribution-intersection reliability estimation method, were performed with the same material type to be used in the system, whether there was statistically enough data in the population, or whether the data population represented all expected factors that can degrade the components' material properties.

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O-13: Reliability risks associated with high packing density can include damage to both the hardware items and soft materials in the parachute pack assembly. This damage can result in weaknesses in the system leading to failures at less than design limit loads or parachute inflation malfunctions that can that exceed the design limit loads for the system, either of which can result in catastrophic failures in the parachute system.

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O-14: Apollo ELS engineers developed a successful method for verifying intact reefing lines prior to flight. A strong monofilament witness line (aka 'catgut') was carefully measured and routed through each reefing cutter during the packing operation. One end was left accessible on the outside of the d-bag. Prior to parachute installation, the witness line was removed and measured. If it was less than the pre-installed length, the pack was rejected. The program always packed four chutes for each mission, in case one was to fail the catgut test (or other pre-flight inspection). The Program ran a comprehensive test and qualification program utilizing the catgut procedure.

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O-15: Strategically located TPS could serve to restrain CPAS packs from entering thermal stand-off zones while providing abrasion protection during deployment (RAO, LAO). Tests would be required to establish if curtains would be a hindrance to FBC separation, and to characterize material performance after exposure to mission environmental conditions.

O-16: The SRB Project packs main parachute canopies in their d-bags in a circular pattern to mitigate the risk of abrasive damage to parachute components during deployment, ref. NASA Engineering Network entry 0836. (RAO only)


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O-17: The stowage routing scheme for the dual-drogue harnesses, on the outside of the FBC and covered with TPS, poses a risk during reentry of a single event of TPS damage resulting in burn damage to two drogue harness legs – one from each drogue harness set.

O-18: Kicker strap concepts that were reviewed used some of the aerodynamic force provided by the drogue parachute(s), to impart a radial force to each of the three main d-bags collectively while they are being extracted, to reduce the risk of near field contact of main d-bags with CM tunnel and gussets, but these may increase the risk of their near field contact with the FBC. Kicker straps may also provide for more synchronous deployment and better load sharing under adverse conditions. (LAO).




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O-19: Kicker straps that use some of the aerodynamic force provided by a *pilot* parachute to impart a radial force to a main d-bag while it is being extracted, may reduce the risk of near field contact of main d-bags with CM tunnel and gussets. (PDO)


O-20: To ensure a robust and reliable design, the Apollo Program proved every part number and every assembly number by test or analysis to certify the system for man-rated flight.

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O-21: To improve the timeline for pad abort, CPAS changed the PTRS in March 2009, to align their requirement for pad abort fault tolerance with GNC requirements. The change was from a requirement of one failed drogue parachute *and* one failed main parachute, to one failed drogue parachute *or* one failed main parachute.



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O-22: For pad abort, the requirement for the LAS is to deliver the CM at an attitude of less than +/-70 degrees prior to drogue mortar initiation. The requirement was established by running Monte Carlo simulations using DSS. Insufficient information was reviewed for the NESC team to assess this result, but the method is unorthodox. If after a LAS hand-off, one drogue fails to fire, the remaining drogue mortar will deploy the confluence ring, riser and pack, and 2-5 seconds later the CM will be released from the FBC. During those 2-5 seconds, the drogue pack may reach line stretch and inflate to its first reefing stage. The drogue will tend to pull the CM apex away from the direction of travel, reducing the angle, but the drogue's three-legged harness, which provides CM stability for a normal reentry, may not be deployed for sufficient time to positively affect CM stability. The requirement at FBC release is +/-50 degrees. The attitude and rates of the CM at FBC release will depend on stochastic factors that may not be fully modeled in simulations. It may be imprudent to conclude that the CM will be within +/-50 degrees attitude at FBC release based *only* on preliminary simulations. FBC release with large CM attitudes and rates will increase the risks of all of the following: pilot parachute entanglement, failure to extract main packs, Near-Field contact of main d-bags, Near-Field contact of main parachute components during extraction from d-bags, and Near-Field contact of main parachute components during deployment. Any of these increased risks increase can result in a failed main parachute.

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O-23: Several known Apollo Test and Analysis reports with data that would be useful to the CPAS S&MA Team for generating reliability estimates cannot be located.

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O-24: The NESC team observes that the following set of architectural options comprehensively reflects many of the team's recommendations. The team recognizes that CPAS personnel are managing a complex problem, wherein each proposed design feature change affects several others, and that there are numerous integration constraints involving other Orion subsystems. The NESC team's comprehensive set of options may (or may not) add mass, but may reduce a number of reliability risks and provide a positive volume budget for future development.


- Four FBC-deployed pilot parachutes.
- Four main parachutes.
  - Four parachutes may open faster than three (with comparable drag area), which could provide more time on the mains after pad abort.
  - One failed main would result in a residual 75% capability rather than 66% capability.
- Four main d-bags that are:
  - smaller
  - less dense
  - less irregularly shaped
  - have a volume reserve

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O-24: (Continued)

- D-bags stowed in the four sectors of the forward bay that do not have drogue mortars.
  - If the four packs use 90% of each sector (4 of 6 sectors X 90% = 60% of forward bay), this allows 10% of each sector for stowage of other items.
  - Using 60% of the forward bay represents a 20% increase in total utilized volume (old, 3 of 6 X 100% = 50% of forward bay, and 60/50 = 1.20).
- Redundant kicker straps on each d-bag to mitigate the risks of geometric lock.
- A 20% increase in total utilized volume could allow:
  - About 5% decrease in the size of each parachute pack. Main packs that are smaller can have simpler shapes, which could reduce risks associated with Near-Field contact and rigging errors. Simpler shapes may also allow simpler retention systems with more reliable release mechanisms.
  - About 5% decrease in each pack's density. Main packs that are less dense have reduced risks of damage from packing.
  - About 5% volume reserve for future growth. Main packs with a growth allowable can accommodate future development growth.
  - About 5% increase in total parachute mass (if mass increase at all). This could allow incorporation of features that resolve parachute structural weaknesses.

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<b>Backup – Reference Material Reviewed</b>	Mike Kelly
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- **Assessed Reference Material**
- **1 Requirements**
  - JSC64355\_Assump\_Memeo.doc
  - JAS63497\_CPAS\_PTRS.doc
  - Deployment Envelope Comparison.ppt
  - PTRS Signed Off 01.16.09.pdf
  - Assumptions Document.doc
  - PTRS Requirements Specification 10.17.08.pdf
  - CX Pyro specification JSC 62809.pdf
  - CxP 70135.pdf
  - NASA-STD-5019.pdf
  - NASA-STD-6016.pdf
  - CxP 70038.pdf
- **2 Design**
  - LAS Well Photo.jpg
  - GN&C Design Databook (LAS Abort).pdf
  - GN&C Block Diagram.pptx
  - CEV Pyro Event Controller Block Diagrams.ppt
  - CEV FBC R&R Mechanism – Design Update (2/2/09).ppt
  - GN&C design Databook (Entry).pdf
  - GN&C Design Databook (iGN&C).pdf
  - LAS Fairing Assembly.ppt
  - CEV FBC R&R Mechanism (ODAC-3POD).ppt
  - Re-entry Sequence DRAFT 01.06.09.xls
- **3 Reliability**
  - CPAS Fault Tree 2-24-09.pdf
  - Reliability Data Critical Review 02.03.09.ppt
  - Preliminary Fault Tree 11.25.08.tif
  - Statistics and Reliability Subteam Notes.ppt
  - CPAS Sys IDR RAESR.doc
  - CPAS Sys IDR PRA.tif
  - CPAS Sys IDR PRA Reliability Predictions .ppt
  - CPAS Sys IDR HA 112508.xls
  - CPAS Sys IDR FTA.tif
  - CPAS Sys IDR FMEA 112508.xls
  - CMO GFE Directive CMOG-CPAS 02-15-09 Main Configuration.ppt
  - Orion Decision Making Process.ppt
  - Airborne\_Org\_Chart.pdf
  - CPAS Revised Functional Team Chart.ppt
  - ESCG – CPAS Org Chart.ppt
  - NASA – CPAS Org Chart.ppt
  - CPAS organization charts.ppt
  - CPAS Project's schedule.ppt

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- **Assessed Reference Material**
- **4 Testing**
  - ESCG-4390-08-SP-DOC-0028\_BASELINEPDF[1].pdf
  - ESCG-4390-08-SP-DOC-0036\_PDFBASELINE[1].pdf
  - ESCG-4390-08-DOC-0029\_Baseline[1].pdf
- **5 Meetings**
  - IDR charts – updated, received 02.02.09.ppt
  - Updated CPAS IDR Charts.ppt
  - CPAS System IDR \*Final\* Presentation.ppt
  - CPAS System IDR Preliminary Charts.ppt
  - Agenda for IDR.ppt
  - Pre-Kickoff Charts 12.03.09.ppt
  - Twist Testing.ppt
  - Single Point Attach Reliability.ppt
  - Pareto WGA Analysis.ppt
  - New Riser Stowage Method.ppt
  - Main Deploy Pro Con.doc
  - Gussett Fairlead Concept.ppt
  - Energy Modulator Analysis.ppt
  - Agenda 012809.doc
  - Pareto WGA Analysis ~ presented by Airborne Systems.ppt
  - CPAS Mel Summary Post IDR, Rev A 012909.doc
  - CPAS Mel Rev A Excel Basis.xls
  - Kokis's chart re ERB decision on single point attach.ppt
- **5 Meetings (cont)**
  - SE&I Agenda 020209.doc
  - Kelly notes from 020209 SE&I IPT.ppt
  - Reliability PRA.ppt
  - Reliability Prediscions.xls
  - Snyder Notes from SE&I IPT.doc
  - Notes from 3.02.2009 SE&I Meeting.doc
  - 2009.03.02 SEI IPT.ppt
  - Snyder Notes from SEI IPT March 16.doc
  - JSC64335\_Assump\_Memo.doc
  - PTRS draft proposed revision 03.16.09.doc
  - Reliability\_FTA.ppt
  - FTA\_Descriptions.doc
  - CPAS summary position on main d-bag shape issues 02.06.09.doc
  - Hardware IPT\_01.28.09\_Nicks's notes.ppt
  - Single Point Attach chart from Hardware IPT meeting 01.21.09.ppt
  - Nicks notes from Hardware IPT 02.04.09.ppt
  - Load Sharing Assumptions.ppt
  - Flight Testing Instrumentation Data Rates Table.xls
  - Drogue Load sensitivity to weight increase.ppt
  - CPAS Hardware IPT Agenda 02-11-09.doc
  - Bob's Notes regarding the Charts from FEB 11 Hardware IPT.ppt

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- |  |   |
|--|---|
| <ul style="list-style-type: none"> <li>• <b>Assessed Reference Material</b></li> <li>• <b>5 Meetings (cont)</b></li> <li>• Update To The DSS Inflation Model.ppt</li> <li>• Drogue Parachute initial Conditions GB.ppt</li> <li>• Drogue Harness Design Dispersions.ppt</li> <li>• CPAS avionics requirements.doc</li> <li>• CPAS avionics capabilities.doc</li> <li>• 20090218 CPAS Hardware IPT Agenda.doc</li> <li>• 03.24.09 S&amp;MS Telecon Definitions document.doc</li> <li>• 03.24.09 S&amp;MA Telecon Charts.ppt</li> <li>• Jims notes from Jacobs/Airborne reliability telecom 02.03.09.doc</li> <li>• 02.03.09 Reliability telecom w/Jacobs and Airborne.ppt</li> <li>• ERB Charts Briefed 03.12.09.pptx</li> <li>• Parachute ERB Briefing 03.02.09.ppt</li> <li>• ERB Orion-09-0355 – CPAS DAC3 Update.pptx</li> <li>• <b>6 Historical Information</b></li> <li>• Apollo Earth Landing Systems Experience Report by Bob West.pdf</li> <li>• Apollo Deployment Envelopes.ppt</li> <li>• Apollo 15 Parachute failure.pdf</li> <li>• Apollo Technical Manual – Reliability.pdf</li> <li>• Apollo Parachute Landing System – Knacke.pdf</li> <li>• Juan Cruz Parachute Course.pdf</li> <li>• Reefing Line Cutters tutorial from MH.ppt</li> </ul> | <ul style="list-style-type: none"> <li>• <b>6 Historical Information (cont)</b></li> <li>• Parachute System Arrangement Sketch – Block I.jpg</li> <li>• Main Harness Attach Fittings Sketch – Block I.jpg</li> <li>• Apollo_17.jpg</li> <li>• Apollo_17_Cover_2.jpg</li> <li>• Apollo_17_Cover_1.jpg</li> <li>• Apollo_16_CM-113_USSRC_2008_RK_5.jpg</li> <li>• Apollo_16_descends_to_splashdown.jpg</li> <li>• Apollo_15_with one failed main parachute.jpg</li> <li>• Apollo_15_CM-112_Dayton_2008_RK_9.jpg</li> <li>• Apollo_15_CM-112_Dayton_2008_RK_8.jpg</li> <li>• Apollo_15_CM-112_Dayton_2008_RK_5.jpg</li> <li>• Apollo_14_5.jpg</li> <li>• Apollo_14_4.jpg</li> <li>• Apollo_14_3.jpg</li> <li>• Apollo_14_2.jpg</li> <li>• Apollo_13_1.jpg</li> <li>• Apollo_8_CMSI_RK_2008_4.jpg</li> <li>• Apollo Soyuz Test Program.jpg</li> <li>• Apollo Soyuz Test Program_2.jpg</li> <li>• Apollo Drogue layout in mortar tube.jpg</li> <li>• Gemini_9_2.jpg</li> <li>• Gemini_9_1.jpg</li> <li>• Gemini_Model.jpg</li> </ul> |
|--|---|

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- **Assessed Reference Material**
- **6 Historical Information (cont)**
- Gemini\_11\_2.jpg
- Gemini\_11\_1.jpg
- Gemini\_Parachute\_System\_Sketch.jpg
- Parachute Deployment Sequence VIDEO CLIP (MOVIE).mov
- Main Parachute Deploy Sequence from Movie.ppt
- Mercury\_MA7\_CMSI\_RK\_2008\_5.jpg
- Mercury\_MA7\_CMSI\_RK\_2008\_4.jpg
- MLAS FBC 02.jpg
- MLAS FBC 01.jpg
- SRB parachute drop test report.tif
- SRB main parachutes installed.ppt
- STS-52.vob
- SRB\_Recovery2.jpg
- SRB\_Recovery.jpg
- SRB\_2.jpg
- SRB\_1.jpg
- SRB\_0.jpg
- SRB Mains Attach Closeup.jpg
- MLAS Design Review – Sep 2008.pdf
- Irvin Design Guide.pdf
- DEPLOYABLE AERODYNAMICS DECELERATION SYSTEMS.pdf
- Dynamic Analysis Of SRB Parachute Systems (Wolf, 1991).pdf
- SRB Recovery Systems.pdf
- **6 Historical Information (cont)**
- Parachute System design Case Study – Huygens.pdf
- Parachute Partial Inversions.pdf
- Parachute Mortar Design.pdf
- Parachute opening Critical Opening Velocity (1971).pdf
- Parachute Definitions, Nomenclature, and Types\_Behr and Lingard.pdf

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## Appendix B.2. Supporting Addendum of Team Assessment for Stakeholder Outbrief of Interim Recommendations 1


This Addendum contains a list of 336 factual statements (FS) and 96 experience-based observations (EO) from the NESC team's first review period (RP-1) which culminated in Outbrief 1 in April 2009.

During RP-1, the CPAS project and its contracted affiliates were working very hard during this time, given a complex design integration problem to converge on an architecture that would result in a robust and reliable system. Design details and requirements evolved rapidly during RP-1. During this dynamic time the assessment team rapidly evaluated a great many design details and project work products.

The NESC parachute subteam members and reliability subteam members were active teaching each other pertinent factual aspects of their respective crafts. In an effort to compile and organize all of the assessed information in a manner that would facilitate the creation of its first set of findings, observations and interim NESC recommendations, the team created the following list of FS and EO.


The list is reproduced in this Appendix to provide the reader insight into the many team discussions that resulted in the first set of findings, observations and interim NESC recommendations. Some of the items in this list may appear to be elementary or obvious statements of fact. These were deliberately captured as building blocks to aid technical understanding across the subteams and to create logical foundations for the team findings, which were derived later.

The list is organized into groups of factual statements and experience-based observations according to the following categories:

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## Organizational Communication

FS-1: Airborne Systems North America (Airborne, aka Irvin Aerospace) is contracted by Jacobs Engineering and Science Contract Group (Jacobs ESCG, aka Jacobs), to provide development data, design data, test hardware, and test data to the CPAS Project.

FS-2: The CPAS Project will deliver the Airborne development data, design data, test hardware, and test data as Government-Furnished Equipment (GFE), to Lockheed Martin (LM).

FS-3: The CPAS team members from NASA Johnson Space Center (JSC), Jacobs, and LM are located in Texas. Airborne is located in California.

FS-4: JSC/Department EA3 and Jacobs share primary System Engineering and Integration (SE&I) responsibilities for the project. JSC/Department EA2 has adjunct SE&I responsibilities. Airborne also has a System Engineering Lead.

FS-5: A chart presented at the December 2008 Initial Design Review (IDR) identified an individual as the “Project Engineer/SE&I IPT Lead” (Integrated Product Team Lead) for Airborne.

FS-6: Jacobs has primary Safety and Mission Assurance (S&MA) responsibilities for the project and JSC/Department NT has adjunct S&MA responsibility.

FS-7: Airborne provides reliability estimates for parachute structures to Jacobs for use in S&MA Fault Tree Analysis (FTA).

FS-8: LM and NASA coordinate program decisions via a Technical Integration Team (TIT).

FS-9: The inclusion of Airborne in the functional organization adds organizational complexity by creating an extended, matrixed organization that is also geographically dispersed.

FS-10: The CPAS functional organization is complex.


FS-11: Organization charts show the Analysis Team to be connected to the project by dotted lines.

EO-1: Dotted lines on organization charts can suggest limited oversight.

FS-12: Organization charts show that LM and NASA have sufficient review boards and panels for assessment of CPAS Project decisions.

FS-13: From December 2008 through March 2009, S&MA fault trees and reliability estimates lagged behind in their representation of the evolving baseline design architecture.

EO-2: Inherent difficulties with communication across a complex, extended, matrixed organization may have contributed to S&MA fault trees and reliability work products that lagged behind design decisions between December 2008 and March 2009.

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EO-3: Prior to the December 2008 IDR, preliminary reliability estimates were communicated to Constellation Program (CxP) decision makers, apparently without caution or explanation about the limitations of their foundation.

EO-4: From December 2008 through February 2009, it appeared that the reliability assessment was seen as a separate task instead of an integrated discipline that improves design decisions.

EO-5: In March 2009, it appeared that coordination between the S&MA Team and the Design team was improving.

FS-14: Operation of CPAS will involve a complex network of events, some serial and some in parallel, that involve numerous system components that must interact with each other different ways during different events. These interactions will vary by choice of architecture.

FS-15: CPAS components will interface with other systems; these interfaces will vary by choice of architecture.

FS-16: Systems with which CPAS interfaces are being designed by teams in various places in the matrixed organization.

EO-6: CPAS architectural design definition would be expected to be iterative during the time leading up to PDR.


FS-17: Minimal interface control documentation was provided for review between December 2008 and March 2009.

EO-7: The complexity of communicating across an extended matrixed organization can hinder thorough investigation of system component interfaces with other systems, which may lead to poor design decisions.

FS-18: PTRS and reviewed documents make no mention of using NASA SP-2007-6105, NASA Systems Engineering Handbook or NPR 7123.1A, NASA Systems Engineering Processes and Requirements.

## **Fault Tree Analyses, Reliability Estimates, Uncertainty, and Reliability Budgets**

EO-8: FTA is a well-established methodology that uses Boolean logic to reduce the Fault Tree structure into the combinations of events (Minimal Cut Sets) leading to failure of a system. Probabilities are computed for individual Minimal Cut Sets, forming the basis for their ranking by importance with respect to their reliability and safety impact. FTA is especially useful when analyzing large and complex systems where manual methods of fault isolation and analysis are not viable.

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EO-9: FTA top level events must be described precisely.

- Defining a top event too broadly leads to an open-ended tree, showing no specific cause or causes for failure.
- Defining a top event too narrowly leads to possible cause omissions.

EO-10: An FTA needs to include all possible weaknesses, faults or failures present in the system that could cause safety hazards or reliability problems. Hardware, software, and human components of the system must be included in the FTA. All interactions between the system components and elements must be fully described in the FTA.

FS-19: IDR presentation stated that the FMECA, PRA and FTA are three independent deliverable requirements for the CPAS program.

- Preliminary results of FTA and PRA were presented in IDR.
- FMECA results were not presented at IDR.

FS-20: The methodology being employed by the CPAS S&MA Team in March 2009 showed exclusive emphasis on the top-down/functional FTA. Consequentially, the Fault Tree is repetitive and lacks specificity at places (e.g., the near identical chute reefing failure modes were repeated seven times for Drogue, Main and Auxiliary chutes).


EO-11: The arrangement between Airborne and Jacobs for performing various reliability analyses and other design assurance functions appears to violate the fundamental reliability principle that reliability is a part of the design process. It has to be built in at the beginning to be most effective and it has to be a real time, interactive and iterative process.

EO-12: It appears that the various Project reliability analyses are being used principally as documentation/verification function after-the-fact, rather than as a design tool to continuously assess and improve the system reliability. The S&MA approach appears to be seeking a static design, which is inconsistent with the level of maturity in the design process with ongoing configuration changes.

EO-13: The current format and functional nature of the FTA makes it difficult to correlate the failure modes to the specific hardware. This makes it difficult to identify where additional analysis and/or testing could be strategically employed to reduce uncertainty in the reliability estimates.

FS-21: Although FTA is a tool to detect the potential system weakness in a complex system, the FMECA (“bottom-up” approach) could be a better tool to qualitatively analyze and scrutinize the CPAS component design.

FS-22: S&MA is maintaining two fault trees, a simple tree with narrative definitions to specify the precise failures included in each box, and a more detailed tree with sub-trees.

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EO-14: Some events in the CPAS deployment sequence will be dependent on other events, some will be independent. The reliability of CPAS will be dependent on the probability of the successful outcome of each event. The probability of the successful outcome of each event will be dependent on the reliability of the system components that participate during each event. Ultimately, design component reliability will drive system reliability.

EO-15: The detailed FTA that can trace failures down to component level is the more valuable version of the two S&MA FTAs.

EO-16: The shortened 'PowerPoint' version of the FTA with a definitions page attached, has limited utility except for a communication tool, and it presents risks of miscommunication.

EO-17: Reliability estimates change and evolve as systems are developed.

FS-23: Lockheed is maintaining a fault tree with integrated risks that include CPAS failures, with the intention to plug in the CPAS tree to the Lockheed tree after CPAS PDR.

FS-24: S&MA has placeholders for integrated failures that relate to systems outside of the CPAS system, including CEV systems.

FS-25: The project S&MA Team FTA starts with undesired events (failures) and builds from the top, down. The S&MA Team plans to develop the PRA data by testing.

EO-18: The Lockheed FTA was reported in a March 2009 teleconference to start with component data and build from the bottom, up.


EO-19: There is value in doing FMEA in addition to PRA.

- PRA process using FTA is a deductive (top down) method useful for analyzing failures
- FMEA is an inductive (bottom up) method
- FTA and FMEA complement each other. FTA could be qualitative or quantitative whereas FMEA is qualitative
- Note: FMECA could be qualitative or quantitative. Mostly NASA does FMEA with an exception of JPL which does FMECA

FS-26: The S&MA fault tree refers to main parachutes A, B, C, which are stowed in sectors identified by Lockheed as B, C, and E, respectively.

FS-27: Between December 2008 and March 2009, the project has occasionally discussed relocating parachutes to other stowage sectors.

EO-20: Asymmetry of main parachute stowage could lead to special risks for individual parachutes. For example, side-by-side mains stowed in sectors B and C might be more likely to pose risk to each other during deployment (entanglement, contact, etc) than they do to the main stowed in sector E. Or, the energy modulators attached to the same FBC beam (above Gusset

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120, between sectors B and C), may interfere with each other, posing reliability risks not present with the d-bag in sector E.

FS-28: The CPAS reliability estimate of 1:217 for more than one main parachute contacting CEV structure during deployment was communicated by S&MA analysts without an estimated or calculated uncertainty or a statement regarding the applicability of SRB data. An estimated value for uncertainty for this risk would have been large, owing to the geometric inapplicability of the SRB data to the CEV system.

EO-21: Communicating reliability estimates without quantitative uncertainties or qualitative uncertainties (e.g., reference system similarity), for the purpose of comparing competing architecture alternatives, can lead to poor design decisions.

EO-22: Communicating inapplicable reliability estimates can result in poor design decisions that can adversely affect system reliability.

FS-29: The CPAS reliability estimate of 1:217 for more than one main parachute contacting CEV structure during deployment was communicated by S&MA analysts without an estimated or calculated uncertainty, through the NASA and Lockheed chains of authority.

FS-30: A Lockheed Engineering Review Board (ERB) assessed that the CPAS system was driving the overall reliability for Orion, by including the CPAS reliability estimate of 1:217 for more than one main parachute contacting CEV structure during deployment.

FS-31: The JSC Director of Engineering asked for this NESC team to conduct an assessment of CPAS reliability estimates (among other objectives), citing the Lockheed ERB finding that the CPAS reliability estimate of 1:217 for more than one main parachute contacting CEV structure during deployment was driving overall Orion reliability.


FS-32: Reliability estimates for drogue and main parachute structural component failures were created by Airborne.

FS-33: Some reliability estimates presented at the IDR in December 2008, were said to have been based on Army, Apollo, Soyuz, and Space Transportation System (STS) SRB data, but that document did not include the lineage and derivation of each estimate.

FS-34: Reliability estimates for drogue and main parachute structural components that were presented at the IDR in December 2008, were said to have come from drop test data, vendor component data, and prediction. Fifteen out of twenty-three estimates were said to have been “by prediction.”

FS-35: Some predicted reliability estimates that were presented at the IDR in December 2008 were computed using a reliability estimation method, wherein a pertinent material strength distribution would be compared to an applied loads distribution. The unreliability of the component is calculated from the area of intersection of these two distributions.



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EO-23: The reliability estimates that were computed by Airborne using the distribution-intersection estimation method may underestimate the risk of failure of those components.

FS-36: The CPAS Project has not proposed the development of test plans to show how reliability estimates based on prediction would be verified/validated.

EO-24: Some reliability estimates were based on results from simulation codes for which it was not clear if rigorous V&V had been accomplished.


FS-37: Reliability estimates for drogue and main parachute structural components that were presented at the IDR in December 2008, included five items with failure rates of 1:10,000 or worse. Three of these were determined by test and two were estimated by prediction.

Determined by test:

- Failure of a drogue parachute with a root cause in some aspect of the packing (1:10,000)
- Failure of a main parachute with a root cause in some aspect of the packing (1: 10,000)
- Failure of a drogue parachute with a proximal cause in some aspect of the parachute failing to extract from the d-bag (1:3,333)

Estimated by prediction:

- Failure of a main parachute with a proximate cause of failure of an unspecified number of attachment joints between skirt structural elements and suspension lines. (1:806)
- Failure of a main parachute with a proximate cause of failure of an unspecified number of vent line attachments. (1:8446)

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FS-38: The following table of failure mode estimates was received from the S&MA team on March 3, 2009.

Failure Mode	Estimate (1/x)	Prediction (1/x)	Rationale
Main / Drogue Confluence Failure	>10M	-	Low number due to proof testing and subsequent post packing X-ray inspections.
Environment Induced Failure	>10M	-	Low chemical concentrations not expected to affect parachutes. Vibration could change the shape of bags causing contact issue. Low number due to vibration qualification.
Rigging Error (Main + Drogue)	100,000	-	Conservative number due to decreased complexity compared to parachute packing.
Far-Field Contact	70,000	-	Failure due to 2 auxiliary failures.
Near-Field Contact	15,696	-	From SRB data for 3 contact chute failures. Nominal case assumed for independent events due to testing activities.
Main Chute Entanglement	1,000,000	-	Estimated 2/3 <sup>rd</sup> s of a twist from 2–3 seconds for deployment supports low number.
Drogue / Auxiliary Entanglement	1,000,000	-	Low number due to minimum twist due to fast deployment.
Skipped Reefing Stage Failure	200,000	-	Low number due to remote chance of packing error, broken reefing line or X-ray test escape from high packing density.
Chute Deployment Failure	-	2.00E+04	Historical Data (lower bound) dominated by parachute packing.
Lead Lag Failure	>10M		Low number due to treatment as structural failure.
Inflation Failure	1,000,000	-	Given successful deployment and vehicle stability, inflation failures historically have been non-issues.
Reefing Cutter Fails to Disreef		4.00E+04	With redundancy (0.995 ea).

EO-25: The project has broadly assessed that chemical concentrations will be low, and so the risk to the parachutes will be low, but the allowable chemical concentration would depend on the specific chemical compound.

FS-39: The project recognizes the risk of vibration changing the shape of d-bags and causing contact with the FBC IML, and expects to mitigate the risk by vibration qualification testing.

FS-40: The project has estimated that the probability of a single parachute contacting CEV or FBC structure is 1:15,696. This is a revised number from the 1:8,205 presented at the December 2008 IDR.

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FS-41: The project estimates that the CM can roll 240 degrees (“2/3<sup>rd</sup>s of a twist”) relative to the drogue-suspended FBC, during the estimated 2–3 seconds between FBC release and line stretch, and uses this to support an estimate of Main Chute Entanglement of 1:1,000,000.

FS-42: The project estimates that the risk of drogue chutes or auxiliary chutes entangling with themselves or which each other during deployment is low, because they are deployed and inflated fast.

FS-42b: Theo Knacke report states “Wind tunnel tests and free fall tests of a full-scale dynamically-similar CM indicated instability in all 3 axis. A preferred short-duration attitude of the CM was nose down at about 135 degrees to the take off (zero degree) attitude”

FS-43: The project estimates the risk of skipped reefing stage at 1:200,000, in part because of a “remote” chance of failing to detect a damaged reefing ring or prematurely triggered cutter using X-ray non destructive evaluation, even at high-packed densities.

F-44: The project lower-bounds the probability of chute deployment failure at 1:20,000 based on historical data. Packing errors are said to be predominantly responsible for deployment failures.

FS-45: Lead/lag failures, the risk of one main parachute beating its cluster mates to the moment of line stretch and inflation so much earlier that it’s loads exceed margins and it fails, is said to be treated as a structural failure, so the probability is set arbitrarily low in this table.

EO-26: The condition of lead/lag could be a design loads driver that could affect both the CM and the parachute. It would not be the results of a failure or an out of spec condition.

EO-27: The probability of a lead/lag deployment event was high for Apollo Block II ELS main parachutes, because they were mortar deployed in different directions. The probability of a lead/lag deployment event may be less for CPAS than for Apollo, for all three architectural main deployment options, because all three main parachutes are deployed in the same direction.


EO-28: The project has assessed inflation failure to be a low risk, with a stable vehicle, but stability is not assured during deployment.

FS-46: The project has predicted that two reefing cutters have a combined reliability to cut a reefing line of 0.995.

## **Applicability of Apollo Geometry for CPAS Near-Field Contact Estimates**

FS-47: Parachute systems in use for aircraft deceleration or aircraft recovery are deployed from stowage spaces that are not geometric similar to the CPAS forward bay.

FS-48: Parachute systems in use for weapons systems are deployed from stowage spaces that are not geometric similar to the CPAS forward bay.

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FS-49: The Apollo CM forward bay had four gussets, equally spaced around the Docking Tunnel which provided four bays. The three main parachute packs were stowed in three of the bays along with its related pilot parachute mortar assembly. The fourth bay contained the drogue parachute mortars and the parachute attach/disconnect fitting. The CEV forward bay is geometrically analogous to the Apollo forward bay in general arrangement, but is divided into six individual sectors rather than four.

FS-50: Each Apollo main d-bag was lifted from its stowed sector by a force provided by an inflated pilot parachute.

EO-29: If deployed in a nominal vehicle attitude, each Apollo main d-bag was extracted from its stowage sector by its inflated pilot parachute in a direction up and slightly away from the docking tunnel wall. The initial velocity vector for main chute extraction was dependant on the attitude of the CM and its relationship with the associated pilot chute when the pilot chute load was applied.

FS-51: For the loosely-attached-pilot-deployed mains architecture option, each CPAS main d-bag will be lifted from its stowed sector by a force provided by a pilot parachute.

EO-30: For the loosely-attached-pilot-deployed mains architecture option, each CPAS main d-bag will be lifted by its inflated pilot parachute in a direction parallel to the tunnel wall.


## **Applicability of SRB Data for CPAS Near-Field Contact Estimates**

FS-52: At the December 2008 IDR, the probability of occurrence of more than one main parachute contacting CM structure during deployment, while being lifted in their d-bags from their stowed locations (for the architecture configuration with main d-bags loosely-attached to the FBC underside with two bag handles each, with integrated energy modulators), was presented as 1:217. This estimate was shown to have been derived from Space Transportation System (STS) Solid Rocket Booster (SRB) data that showed 3 occurrences out of 651 opportunities, of a single SRB parachute failing from contacting the Main Parachute Support System (in its frustum) or the frustum edge.

FS-53: The probability of a single SRB parachute component being damaged by contact (drag across, slide along or strike against) the Main Parachute Support System (in its frustum) or the frustum edge, reduced over time due to mitigating actions taken by the SRB project. The 651 opportunities that were considered to calculate the 1:217 value is not a true representation of one specific configuration, nor any configuration that suitably represents CEV.

FS-54: The CPAS FBC is analogous in function to the SRB frustum, but differs geometrically in significant ways.

FS-55: The CPAS FBC has six radial beam structures on its underside. These are not large enough to extend down between stowed main parachutes.

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FS-56: The SRB frustum has three deep isogrid panels and three bipod struts on its underside. This assembly, known as the SRB Main Parachute Support Structure, separates the three stowed main parachute d-bags from each other.

FS-57: For all three principal CPAS main parachute deployment architectural configurations, CPAS main parachute d-bags are lifted from their stowed positions to begin the deployment of their packed contents from the bottom. There is no comparable “lifting” event for SRB deployment. SRB main parachutes deploy directly from d-bags that are rigidly attached inside the frustum.

FS-58: For all three principal CPAS main parachute deployment architectural configurations, any CPAS main parachute d-bag may physically contact (drag across, slide along or strike against) the CEV tunnel, up to two CEV gussets, and up to two LAS Wells. This risk only exists for a short time while a d-bag is being lifted from its stowed location, until it has cleared the top of the tunnel. The top surface of the SRB rocket has no structures analogous to the CEV tunnel, gusset or LAS Well.

FS-59: For all three principal CPAS main parachute deployment architectural configurations, as a main parachute’s riser begins to play out of its d-bag, it can physically contact (drag across, slide along or strike against) the CEV tunnel, a CEV gusset, or a LAS Well. The top surface of the SRB rocket has no structures analogous to the CEV tunnel, gusset or LAS Well.

FS-60: The SRB reliability data of 1:217 is not applicable to the risk for CPAS of main parachute d-bags contacting the CEV tunnel, gussets or LAS Wells during extraction from their stowed position.


FS-61: The SRB reliability data of 1:217 is not applicable to the risk for CPAS of main parachute risers contacting the CEV tunnel, gussets or LAS Wells during deployment from their d-bags.

FS-62: The SRB reliability data of 1:217 is not applicable to the risk for CPAS of main parachute components contacting the underside of the FBC, in the “loosely attached” main parachute deployment architectural configuration.

FS-63: The SRB reliability data of 1:217 is not applicable to the risk for CPAS of main parachute components contacting the underside of the FBC, in the “pilot chutes loosely attached” main parachute deployment architectural configuration.

FS-64: The SRB reliability data of 1:217 is somewhat applicable to the risk for CPAS of main parachute components contacting the underside of the FBC, only in the “rigidly attached” main parachute deployment architectural configuration.

- This applicability may be limited by consideration of differences between the Orion CM’s dynamic behavior relative to the FBC after separation, compared to the STS Shuttle SRB’s dynamic behavior relative to its frustum after separation.

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## Main Parachute Deployment Bags and Packing Issues

FS-65: The main deployment bags (d-bags) have an irregular shape, with concavities and sharp corners, which could be a factor in packing the parachutes at high densities without inflicting damage.

FS-66: The main d-bags closure flaps are on the bottom, facing the deck when stowed, which could have an effect on parachute packing since they will be packed into a sloping surface.

FS-67: The shape of the main d-bag poses risks of non-homogeneous density and difficulty in achieving consistent results from pack to pack.

FS-68: It may be necessary to imbed stiffeners in the main d-bags to help them maintain their shape.

FS-69: In March 2009, the project discussed an optional pack shape that replaced the concavity feature with a faceted corner. This was being coordinated with Lockheed who would have to redesign the shape of the LAS Wells to accommodate it.

FS-70: The system requirement is 38 lb/ft<sup>3</sup> maximum pack density for the main parachute pack assembly.

- [JSC64335, I.CM.CPAS.101] - The CM will provide volume to ensure CPAS main parachute packing density is less than or equal to 609 kg/m<sup>3</sup> (38 lbm/ft<sup>3</sup>). Rationale: This general requirement requires CPAS to fit within the volume defined by the forward bulkhead and FBC. The volume provided by CM will not require packing the mains to the density of more than 609 kg/m<sup>3</sup> (38 lb/ft<sup>3</sup>).


FS-71: The projected pack density for the main parachute is in the high 40 pounds per cubic ft range, for all architectural options under consideration.

EO-31: There is expert consensus that pack density over 40 lb/ft<sup>3</sup> creates added reliability risks.

FS-72: Reliability risks associated with high packing density can include damage to both the hardware items and the soft materials in the parachute pack assembly. This damage can result in weaknesses in the system leading to failures at less than design limit loads or parachute inflation malfunctions that can exceed the design limit loads for the system, either of which can result in catastrophic failures in the parachute system. These risks include:

- A bent reefing ring than can cut a reefing line and result in a skipped reefing stage
- A bent reefing ring than can damage and weaken a reefing line and result in premature disreefing
- A bent reefing ring than can damage other textile material packed adjacent to it, and result in suboptimal canopy performance



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- A damaged reefing line cutter that cuts a reefing line, and results in a skipped reefing stage
- Two damaged reefing line cutters on one reefing line that cannot actuate, and prevents disreefing of that stage (or any subsequent stage)
- Damaged textiles during extraction from their d-bag, due to heat from friction
- Reduced probability of detection (POD) of X-ray inspection for damaged pack contents

FS-73: According to the Apollo ELS Experience Report, during development of the Apollo Block II ELS, as the density of the parachute packs increased, the amount of damage to the parachutes increased.

EO-32: Pack density in the high 40 pounds per cubic ft at this stage of the system development program leaves no room for error, design growth or vehicle growth (with associated parachute growth), all which occurred during Apollo.


EO-33: Allowing for a 45lb/ft<sup>3</sup> density at this stage of the design could paint the designers into a corner. It appears a challenge for CPAS to achieve the reliability necessary for a manned system with the volume currently provide for three main parachutes, below the required pack density.

FS-74: Apollo ELS engineers developed a successful method for verification of intact reefing lines prior to flight. A strong monofilament witness line (aka ‘catgut’) was carefully measured and routed through each reefing cutter during the packing operation. One end was left accessible on the outside of the d-bag. Prior to parachute installation the witness line was removed and measured. If it was less than the pre-installed length, the pack was rejected. The program always packed four chutes for each mission, in case one was to fail the catgut test (or swell inspection, stitch inspection or other pre-flight inspection). The method proved to be successful. Apollo ran a comprehensive test and qualification program for the catgut procedure, because of their recognition that loss of more than one main chute would result in LOC.

FS-75: Apollo ELS reliability was highly dependent on quality inspection and the skill and experience of the inspectors. The skill levels and the procedures were developed and proven during the ELS development and qualification program and imposed through the operational program. Procedure developers, who had helped develop the inspection techniques, later performed operational inspections.

FS-76: The NASA Engineering network, lessons learned database, entry 0836, submitted in 1994, documents that to mitigate observed abrasive damage to SRB main parachute canopies during deployment, the SRB parachute packing procedure was revised from a “zigzag” pattern to a “circular” pattern.



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## Pack Retention

FS-77: For the loosely-attached mains architectural option, The Main Parachute retention system is comprised of two donut ties and two electrically initiated cutters, either one of which can cut both ties. The two cords retain the packed main parachutes on its upper surface at six points. The six points are ends of six retention straps whose other ends are attached to the CM structure at locations beneath the pack and behind it on the tunnel. The retention scheme does not appear to allow for growth due to handling, thermal and humidity cycles. A failure at one of the retention points will result in the loss of 50 percent of the overall retention capability. The release of the retention system is based upon actively initiating two electrically initiated cutters. The failure to release the retention system will result in locking a packed main parachute into its stowage sector, consequently resulting in failure to deploy one main parachute.

FS-78: The Apollo retention system was a quick release system that fully covered the packed main parachute, retaining it every couple of inches along the perimeter.

FS-79: For the pilot-deployed mains architectural option, the project redesigned the retention release concept to eliminate the electrically initiated cord cutters, and replaced them with a pair of redundant cut-knives.

## Volume Budget

FS-80: Apollo Block II ELS main parachutes were nominally 83.5 ft diameter inflated, compared to 116 ft for CPAS main chutes. Dimensions are approximately in proportion for vehicle size.


FS-81: Apollo Block II ELS main suspension lines were nominally 120 ft long, compared to 133 ft for CPAS main suspension lines. Dimensions are approximately in proportion for vehicle size.

FS-82: Apollo Block II ELS main risers were nominally 7.8 ft long (6.5 ft steel and 1.3 ft fabric), with 3.5 ft fabric bridle legs. This compares to 113 ft for CPAS main risers (97 ft suspension lines plus 16 ft harness length). The total trailing distance of the Apollo main chute skirt behind the C/M is approximately 131 feet versus the 113 feet for the CPAS. This can have an effect on both the inflation characteristics and the stability of the inflated canopies.

FS-83: Apollo ELS Block II devoted 75% of forward bay volume to its three main packed d-bags (including most of the riser lengths) and the three pilot parachute mortars for deploying the mains.

FS-84: Apollo ELS Block II devoted 25% of forward bay for its two drogue mortars, its single-point attach fixture (also known as the 'flower pot'), and other hardware not related to ELS.

EO-34: An estimated allocation of forward bay volume for Apollo Block II ELS components other than d-bags is 5% (of total) for each of two mortars, and 5% (of total) for flower pot fitting.

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FS-85: If the “5% for each mortar and 5% for flower pot” estimate is accurate, then the Apollo vehicle used approximately (  $75 + 5 + 5 + 5 =$  ) 90% of total available volume of forward bay for the Block II ELS, and 10% of available volume for other hardware not directly associated with the ELS.

FS-86: All of the Orion CPAS architectural options under consideration between December 2008 and March 2009 devoted 50% of the forward bay volume (sectors B, C and E) for the three main packed d-bags (including much of the riser lengths but excluding components in the stowage container). None of the architectural options under consideration had pilot parachute mortars for deploying the mains.

FS-87: All of the CPAS architectural options under consideration between December 2008 and March 2009 used a portion of two sectors for two drogue mortars (one each, in sectors A and F).

EO-35: An estimated allocation of forward bay volume for each of two CPAS mortars for CEV, is 10% (of total), regardless of CPAS architectural option.

FS-88: The harnessed-mains CPAS architectural option uses a portion of Sector D, for a stowage container for one confluence fitting, one rotation torque limiter, excess lengths of three main risers, and for the three main harness legs.

EO-36: For the harnessed-mains CPAS architectural option, an estimated allocation of forward bay volume for the CPAS stowage container and its contents is 5 percent (of total).

EO-37: The single-point-attach CPAS architectural option may require one or more small storage containers for excess lengths of the three main risers and for one rotation torque limiter. Risers will be longer in this option to account for lost length of harness legs.


EO-38: An estimated allocation of forward bay volume for the CPAS stowage container and its contents is 5% of total, for the single-point attached mains architectural option

FS-89: Orion CEV uses approximately (  $100 - 50 - 20 - 10 =$  ) 20 percent of available volume for other hardware not directly associated with CPAS and approximately 80 percent of available volume for CPAS.

EO-39: Compared to Apollo in terms of percent of available volume in the forward bay, assuming scalability, Orion is using approximately twice as much volume for items not associated with its parachute recovery system. The parachute recover system is a critical system for crew survival.

FS-90: All of the CPAS architectural options apportion components among 4 sectors, B, C, D, and E.

FS-91: CPAS Project charts indicate previous discussion of moving main d-bags from current bays (B, C, and E) to three other bays, suggesting some decisional control remains with respect to the Lockheed CEV forward bay arrangement.

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FS-92: Concern with “geometric lock” during extraction (d-bag physical contact with tunnel, gussets, and LAS Wells that is so significant as to prevent extraction) is cited in project charts as the principal reason to not consider alternative bays for main d-bag stowage.

EO-40: Relocating main d-bags to other sectors is likely constrained by design decisions made by the Orion CEV project that are unrelated to CPAS, but these were not included in the material reviewed by the NESC team.

FS-94: The size of the CPAS main parachutes is principally driven by pad abort loads and vehicle weight. The volume of the packed main parachutes d-bags is dependent the size of the parachute and the density to which it is packed.

FS-95: Throughout the development of Apollo, changes being made to vehicle systems and structures required continuous improvement in volumetric efficiency of the ELS main parachute packs. Demands increased but available volume did not.

EO-41: Unknown issues during ongoing development of the CPAS system may result in increases in the main parachute volume needs.

FS-96: Unknown issues during ongoing development of the CEV by Lockheed may adversely affect the volume available


FS-97: In the single point attach architectural option, stowage of excess main risers in Sector D, with attachment on the 0° gusset, poses riser routing challenges that may affect the reliability of deployment.

## Forward Bay Cover

FS-98: The NASA Engineering Network, Lessons-Learned database, entry number 0836 submitted in 1994, indicated that abrasive damage was observed to have occurred to SRB main parachute canopies during deployment, from contact with the frustum and MPSS. Early in the STS program, TPS material was installed around the perimeter on the underside of the SRB frustums, to fill the volumes between the two lowest frustum ring frames, to provide a smooth contact surface should the main chutes contact the frustum during deployment. Later, this TPS material was replaced with a fabric curtain, to perform the same function. Foam material was also added to the MPSS bipod struts, to prevent damage from parachute components contacting the MPSS during deployment.

EO-42: Apollo engineers assessed risks of abrasion, friction damage, hang-up objects and sharp edges and addressed each one by proving it did not exist or by incorporating abrasion protection.

EO-43: Parachute components that are deployed from a d-bag that is rigidly attached inside a FBC can contact the sides of the FBC during deployment, and this contact can be exasperated by the dynamic behavior of the two bodies during separation.

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FS-99: Standoff distance and/or insulation is required between FBC and the various parachute system components in the forward compartment to protect against damage due to thermal environment during reentry.

FS-100: Standoff distance is required between LAS Wells and main d-bags to protect against damage due to thermal environment during reentry.

FS-101: Intentionally blank. Superseded by revision to F-99.

FS-102: Main d-bag restraint system is complex, due to complex main d-bag volumetric shape.

FS-103: Vibration during launch or other dynamic events that occur prior to or during reentry can cause stowed d-bag surfaces to enter the stand-off volume and remain there for reentry, if restraint systems are insufficient. This poses risk of damage to the d-bag and its contents (canopy, suspension lines, risers) due to thermal environment during reentry.

FS-104: Vibration during launch or other dynamic events that occur prior to or during reentry can cause stowed and restrained risers and harness legs to enter the stand-off volume and remain there for reentry, if the main d-bags have moved.

FS-105: Commercially available polyimide foam has insulation qualities, mechanical and thermal performance and is light weight. These make polyimide foams candidate materials for installation between FBC and main d-bags, to act as TPS and as supplemental restraint.


FS-106: Commercially available polyimide foam has insulation qualities, mechanical and thermal performance and is light weight. These make polyimide foams candidate materials for installation between LAS Well and main d-bags, to act as TPS and supplemental restraint.

FS-107: Aluminized fiberglass sleeves have insulation qualities and light weight that make it candidate TPS material for protection of textile risers and harness legs that are stowed beneath the FBC that may become at risk of damage due to thermal environment near the FBC IML during reentry, if d-bags have shifted.

FS-108: The Ares I-X flight test project wrapped aluminized fiberglass around first stage risers and riser attach spools to protect them from expected thermal environments associated with its skirt extension / forward skirt separation event.

EO-44: Curtains installed for protection of d-bags against physical damage could become a hindrance to d-bag extraction unless it is securely attached to the FBC, and therefore removed from the forward bay at FBC release.

EO-45: TPS installed for protection of d-bags against thermal damage could become a hindrance to d-bag extraction unless it is securely attached to the FBC, and therefore removed from the forward bay at FBC release.

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FS-109: A review of CPAS preliminary design details reveal a risk of heat damage to main parachute risers from high temperatures at the FBC IML during reentry - if the bottom ends of the risers are stowed on CEV gussets in close proximity to the FBC IML.

FS-110: A review of CPAS preliminary design details reveal a risk of heat damage to main parachute risers from high temperatures transmitted from the LAS wells during reentry - if the bottom ends of the risers are stowed on CEV gussets in close proximity to the LAS wells.

## **Drogue Deploy Envelope**

FS-111: CPAS drogue deploy envelope was developed using Monte Carlo simulations.

FS-112: The drogue deploy envelope is comprised of overlapping zones for pad abort, ascent abort, and nominal reentry.

FS-113: The drogue deploy envelope Points 4 and 5 were relocated in March 2009. Point 4 was moved from 53,000 ft at 99 psf to 45,000 ft at 150 psf. Point 5 was moved from 32,000 ft at 167 psf to 32,000 ft at 150 psf.

FS-114: The drogue deploy envelope zones are dissimilar from those for the Apollo drogue deploy envelope.

EO-46: The drogue deploy envelope establishes candidate flight test data points.

## **Drogue and Main Parachute Construction and Failure Risks**

FS-115: The CPAS drogue parachutes are variable porosity conical ribbon chutes. The Drogue Parachute Drag Surface incorporates “Rip-Stops” to preclude tear propagation.

FS-116: The CPAS drogue canopies are nominally 23 ft diameter. According to Project analysts, the CPAS drogue size is driven by high altitude aborts, with high q and high weight.


EO-46b: Drogue size may be driven by CM stabilization and deceleration requirements throughout the recovery system operating envelope. The rate of descent on the drogues will vary depending on the altitude. The basic requirement is to stabilize the CM and bring it into the acceptable conditions for main parachute deployment.

FS-117: According to Project analysts, the CPAS drogue size was determined by  $q=45$  psf at terminal rate of descent 9(33 fps) with 18k load under on drogue chute.

FS-118: The CPAS drogue canopies’ drag coefficient are nominally 0.57

FS-119: The drogue riser and harness legs are constructed from multiple plies of Kevlar<sup>®</sup> webbing (project infers that this improves reliability).

FS-120: The drogue harness legs are nominally 16 ft. long.

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FS-121: IDR charts (revised Feb 2009) show the Drogue risers are nominally 65.4 ft. long.

FS-122: CEV-LRS-08-004 Rev A (Jan 2009), “ODAC-3 Parachute Model Memo” pg 10, shows the riser lengths to be 48.8 ft long

FS-123: IDR (Feb 2009) and CEV-LRS-08-004 Rev A (Jan 2009) are not consistent with respect to drogue riser length.

FS-124: The CPAS drogue suspension lines are nominally 34.5 ft. long.


FS-125: The length of a Drogue harness leg plus a Drogue riser plus a Drogue suspension line is of sufficient total length to meet the wake rule of thumb of four to six times the forebody diameter, cited from Section 5.2.2 from Knacke page 5-21.

FS-126: The table of drogue parachute margins presented in the IDR charts indicates the use of a variety of textile materials of various strengths for a variety of parachute components. Nylon Ribbon, Kevlar<sup>®</sup> Tape, and Kevlar<sup>®</sup> Cord are conventional materials for parachute systems. Vectran Cord has been used in parachute systems, but is a more recently developed material; it is indicated for use as “soft links.”

FS-127: Vectran is a thermotropic (melt spun) liquid crystal copolyester fiber produced by Kuraray Co., Ltd. (Fort Mill, SC). With comparable yarn tenacity to Kevlar<sup>®</sup> 29, it has better flex-crack/abrasion resistance. Kevlar<sup>®</sup> fibers are more readily damaged by flexing and sliding against themselves, when a fabric is folded. While Kevlar<sup>®</sup> offers more strength retention at higher temperatures than Vectran, Vectran retains its full strength upon cooling and actually gets stronger at low temperatures. (ref- Development and evaluation of the mars pathfinder inflatable airbag landing system)

FS-128: Vectran offers less strength retention at high temperatures than Kevlar<sup>®</sup>.



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DROGUE COMPONENT	Plies	IDR – DECEMBER 2008	Plies	FEB - 2009
Crown Ribbons	1	PIA-T-5608 2" 300-lb Nylon Ribbon	1	PIA-T-5608 2" 300-lb Nylon Ribbon
Mid Ribbons	1	PIA-T-5608 2" 300-lb Nylon Ribbon	1	PIA-T-5608 2" 200-lb Nylon Ribbon
Skirt Ribbons	1	PIA-T-5608 2" 300-lb Nylon Ribbon	1	PIA-T-5608 2" 200-lb Nylon Ribbon
Verticals	1	PIA-T-5608 0.63" 90-lb Nylon Ribbon	1	PIA-T-5608 0.63" 90-lb Nylon Ribbon
Radials	1	PIA-T-87130 1" 4K Kevlar® Tape	1	PIA-T-87130 1" 4K Kevlar® Tape
Vent Band	2	PIA-T-87130 1" 6K Kevlar® Tape	2	PIA-T-87130 1" 6K Kevlar® Tape
Skirt Band	1	PIA-T-87130 1" 4K Kevlar® Tape	1	PIA-T-87130 1" 4K Kevlar® Tape
1st Stage Reef Line	1	PIA-C-87129 4K Kevlar® Cord	1	PIA-C-87129 5K Kevlar® Cord
2nd Stage Reef Line	1	PIA-C-87129 5K Kevlar® Cord	1	PIA-C-87129 4K Kevlar® Cord
Suspension Line	1	PIA-C-87129 4K Kevlar® Cord	1	PIA-C-87129 4K Kevlar® Cord
Soft Links	4	4,500-lb Vectran Cord	4	4,500-lb Vectran Cord
Riser	8	PIA-T-87130 1.75" 20K Kevlar® Tape	8	PIA-T-87130 1.75" 20K Kevlar® Tape
Harness	8	PIA-T-87130 1.75" 20K Kevlar® Tape	6	PIA-T-87130 1.75" 20K Kevlar® Tape

FS-129: Between December 2008 and March 2009 updates to this data, analysts increased the required strength of the first stage drogue reefing line, decreased the strength of the second stage drogue reefing line, and decreased the numbers of plies required in the drogue harness legs.

FS-130: The main parachutes are quarter-spherical ring sail parachutes. The Main Parachute Drag Surface incorporates Leading and Trailing Edge reinforcement on all of the individual panels. These reinforcements act as “Rip-Stops” to preclude tear propagation.

FS-131: The Main canopies are nominally 116 ft diameter. The size is driven by pad aborts, point 7 on the drogue deploy envelope, wherein drogues are released along with the FBC while the drogues are still at the first reefing stage. (Low altitude, low q, high Mach.)

FS-132: Charts from the IDR (briefed Dec 8, 2008 and revised in Feb 2009) and charts from the ERB Orion-09-0355 (Mar 12, 2009) show the main canopies’ combined drag coefficient as 0.94 for 2 chutes and 0.97 for 3 chutes.


FS-133: The ODAC-3 Parachute Model Memo, CEV-LRS-08-004 Rev A (Jan 2009), pg 11, shows the main canopies’ combined drag coefficient 0.718 for 2 chutes and 0.896 for 3 chutes.

FS-134: IDR (Feb 2009) and ERB charts are not consistent with CEV-LRS-08-004 Rev A (Jan 2009), with respect to main chute drag coefficients

FS-135: The main parachutes Riser and Harness Legs are constructed from multiple plies of Kevlar® webbing.

FS-136: The Main three harness legs are two at 19 ft long, and one at 16 ft. long.



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FS-137: the Main risers are nominally 97 ft for the harnessed-mains architectural option. The Main risers will be longer length for the single-point attachment architectural option, but not known.

FS-138: The Main suspension lines are nominally 133 ft. long.

FS-139: The length of a Main harness leg plus a Main riser plus a Main suspension line is of sufficient total length to meet the wake rule of thumb of four to six times the fore-body diameter, cited from Section 5.2.2 from Knacke page 5-21.


FS-140: The table of main parachute margins presented in the IDR charts indicates the use of a variety of textile materials of various sizes and strengths, for a variety of parachute components. Nylon rip-stop cloth, Kevlar® Tape, Nylon Webbing, and Kevlar® Cord are conventional materials for parachute systems. Vectran Cord has been used in parachute systems, but is a more recently developed material; Vectran cord is indicated for soft links and vent hoops.

FS-141: Vectran offers less strength retention at high temperatures than Kevlar®. (repeat)

MAIN COMPONENT	Plies	IDR – DECEMBER 2008	Plies	FEB - 2009
Crown Rings	1	PIA-C-7350 150-200 CFM 3.5-oz Cloth	1	PIA-C-7350 150-200 CFM 3.5-oz Cloth
Mid Rings and Sails	1	III 820201 25 CFM 2.25-oz Cloth	1	III 820208 80-120 CFM 1.1-oz Cloth
Skirt Sails	1	III 820200 40 CFM 1.17-oz Cloth	1	III 820208 80-120 CFM 1.1-oz Cloth
Radials	1	PIA-T-87130 1" 1.5K Kevlar® Tape	1	PIA-T-87130 1" 1.5K Kevlar® Tape
Vent Hoop	3	5,250-lb Vectran Cord	3	5,250-lb Vectran Cord
Vent Band	1	PIA-W-4088 1" 2.5K Nylon Webbing	1	PIA-W-4088 1" 2.5K Nylon Webbing
Skirt Band	1	III 119000 1" 1K Kevlar® Tape	1	PIA-T-87130 1" 1.5K Kevlar® Tape
1st Stage Reef Line	1	PIA-C-87129 4K Kevlar® Cord	1	PIA-C-87129 5K Kevlar® Cord
2nd Stage Reef Line	1	PIA-C-87129 4K Kevlar® Cord	1	PIA-C-87129 4K Kevlar® Cord
Suspension Line	1	PIA-C-87129 1.5K Kevlar® Cord	1	PIA-C-87129 1.5K Kevlar® Cord
Soft Links	4	4,500-lb Vectran Cord	4	4,500-lb Vectran Cord
Riser	8	PIA-T-87130 1.75" 15K Kevlar® Tape	8	PIA-T-87130 1.75" 20K Kevlar® Tape
Harness	14	PIA-T-87130 1.75" 20K Kevlar® Tape	18	PIA-T-87130 1.75" 20K Kevlar® Tape

FS-142: Permeability of cloth is measured in units of cubic feet of air per minute per square foot, abbreviated CFM.

FS-143: Between December 2008 and March 2009, project analysts apparently reduced the required weight of the cloth for the mid rings, mid sails and skirt sails; increased the required strength of the skirt band and the first stage main reefing line; and increased the numbers of plies required in the main harness legs from 14 to 18.

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FS-144: Information presented at the December 2008 IDR indicated that the parachute design methodology will be:

1. Begin with the Gen-1 Drogue and Main parachute designs as basis for the Gen-2 designs.
2. Develop parachute loads from trajectories.
3. Distribute the loads across parachute elements.
4. Apply Design Factors (DF) to loads to determine required element strength.
5. Select elements from known available webbings, cords and cloths based on required element strength.
  - a. Consider that custom material specifications could be more mass efficient.
6. Build up parachute weight using material specification weights.

FS-145: Information presented at the December 2008 IDR indicated that the Design Team would apply a Safety Factor (SF) of 1.6 to all components except those whose failure “could result in catastrophic failure.” These critical elements have a 2.0 SF:


- Soft links
- Drogue vent band
- Main vent hoop
- All reefing lines
- All risers
- Main harness legs

FS-146: Knacke Parachute Recovery Systems Design Manual, Table 6-7, recommends a Safety Factor (SF) of at least 1.6 and a Design Factor (DF) of 2.21, for all elements of parachute assemblies used for manned vehicles.

FS-147: The Irvin Recovery Systems Design Guide, Table 8.6, recommends a SF of 1.35 and a DF of 2.3 for manned systems.

FS-148: The DF is equal to the SF divided by the Allowable Strength Factor (Ap). According to the Irvin Design Guide, AFFDL-TR-78-151, page 413-414, the Ap is the product of seven individual allowable strength factors, all multiplied by the cosine of the line or riser convergence angle from the axis of loading.

- Joint or seam efficiency
- Abrasion and wear

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- Moisture absorption due to humidity, etc
- Fatigue due to repeated loading or use
- Temperature
- Vacuum
- Asymmetrical or unequal loading

FS-149: The Table of Main Parachute Margins presented at the IDR in December 2008 showed the Main Vent Band DF of 2.21, which meets the Knacke guideline, but does not meet the Irvin guideline.

EO-47: Joint efficiency is a critical component of the Allowable Strength Factor calculation.

FS-150: Information presented at the December 2008 IDR indicated that the Design Team assesses that many Gen-1 joint efficiencies assessed to be below 80% could “be improved to at least 80%.”

FS-151: Information presented at the December 2008 IDR indicated that the Design Team assesses that the main riser and the main harness joint efficiencies cannot be improved to at least 80%, because they are driven by pin loads.

EO-48: O: Demonstrating V&V for drogue and main parachute structures could result in a significant amount of testing. If all joints are tested, this could tax test facilities.

EO-49: Review of Gen 1 test reports suggests that in 2007 and 2008 there was a lack of a systematic process in establishing the basis for and the conduct of testing.

## Parachute Attach Fittings


FS-152: The Apollo ‘flower pot’ fitting attached to the CM at 0° (the ‘crew heads up’ direction), mid-way between two gussets (45° and 315°). The fitting reacted drogue and main parachute loads.

EO-50: Six CEV CM LAS Wells are sized for substantial loads from launch abort conditions.

FS-153: LAS Wells are located at the base of each of the six forward bay gussets.

FS-154: Six CEV CM forward bay gussets (Al-Li) are FSW welded along two orthogonal sides, to the forward bay bulkhead (monolithic integrally machined Al-Li structure) and to the tunnel (monolithic integrally machined Al-Li structure).

FS-155: For all CPAS architectural options, the drogue parachute loads are transmitted through the FBC and reacted by the CM gussets at 60°, 180°, and 300°.

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FS-156: For the CPAS harnessed-mains architectural option, main parachute loads are reacted at the base of CM gussets at 0°, 120 °, and 240 °.

FS-157: For the CPAS single-point attach main architectural option, three main parachute attach fittings are integrated into the CM's 0° gusset, midway up its length.

EO-50b: Integrating three main parachute attach fittings are into the CM's 0° gusset, midway up its length may not allow for sufficient riser excursion during parachute deployment.

FS-158: For the CPAS single-point attach main architectural option, CPAS assumes load share main attach fitting load share of 50% / 25% / 25%.

EO-50c: The CPAS load share assumption on main attach fittings of 50% / 25% / 25% will have to be verified by appropriate main chute cluster tests.

FS-159: According to Airborne charts from a Feb 3, 2009 presentation, Apollo designed main attach fittings (flowerpot assembly) to the assumed load share of 40% - 40% - 20%.

EO-50d: The Apollo load share assumption on main attach fittings of 40% - 40% - 20% were verified by instrumented aerial drop tests.

EO-51: For the CPAS single-point attach main architectural option, if main risers have wrapped more than one complete turnaround each other during deployment, the loads from multiple inflating canopies may all react though one riser beneath the twist point. This could affect torque limiter function and could result in high loads on just one attach fitting.


EO-52: If significant design changes are required for to the CEV CM 0° Gusset to accommodate the CPAS single-point attach architectural option, detailed coordination with Lockheed designers and analysts is essential to recognize integration issues as soon as possible. The 0° Gusset may need to be assessed as Design for Minimum Risk (DFMR).

## Deployment Bag Handles and Energy Modulators

FS-160: In the loosely-attached mains architectural option described in the December 2008 IDR, each main d-bag is attached to the FBC by four bag handles of 20,000 lb Kevlar® Tape each, two on each side of the d-bag.

FS-161: In the loosely-attached mains architectural option described in the December 2008 IDR, Energy Modulators are incorporated into the bag handles, to reduce snatch forces.

EO-53: The geometry of the d-bags suggests that the d-bags centers of gravity will be offset outboard (radially, away from the tunnel) from the attach locations of the four bag handles. If the d-bags centers of gravity are outboard from the handles, then the extraction forces acting on the d-bag handles as the bags are lifted, would impart a pitching moment on the bags. This moment may be sufficient for the lower back edge of all of bags to contact (slide along or strike against)

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the tunnel during extraction. This could be a common cause source of damage to all three main d-bags.

FS-162: Energy modulators are sewn-together double-lengths of fabric that as they are loaded, tear apart. The tearing spreads the energy of a rapidly applied force over a longer period of time.

FS-163: Energy modulators are incorporated into d-bag bag handles for the loosely-attached mains architectural option.

FS-164: The effectiveness of energy modulators in this application may be reduced if a d-bag's extraction from its stowed location is delayed by contact (drag across, slide along or strike against) with CM structure.

## Kicker Straps

FS-165: Kicker strap concepts were shown that use kinetic energy from the separation of the FBC away from the CM after release, provided by drogue parachute forces, to impart energy to main d-bags in a radial direction while they are being extracted, for FBC-deployed main parachute architectural options.

FS-166: Kicker straps as envisioned for FBC-deployed main parachute architectural options may reduce the risk of near field contact (drag across, slide along or strike against) of main d-bags with CM tunnel and gussets during extraction from their stowed locations.

FS-167: Kicker straps as envisioned for FBC-deployed main parachute architectural options may not reduce the risk of near field contact (drag across, slide along or strike against) of main d-bags with CM LAS Wells during extraction from their stowed locations.


FS-168: Kicker straps as envisioned for FBC-deployed main parachute architectural options may increase the risk of near field contact of main d-bags with FBC structure, by imparting a pitching moment as they impel d-bags radially away from the CM, with the FBC still proximal.

EO-53b: Kicker Strap concepts that use some of the energy from the force provided by the pilot parachute at inflation, to impart energy to main d-bags in a radial direction while they are being extracted should be physically conceivable.

## Rotation Torque Limiter

FS-169: The PTRS requires CPAS to limit the torque required to roll the CM about the gravity vector prior to landing while suspended by its main parachute system, to less than 450 ft-lbs., to allow the RCS to maintain the crew's feet oriented towards the horizontal direction of travel prior to landing.

FS-170: For the harnessed-mains architectural option, a rotation torque limiter would stow beneath the confluence fitting in a stowage container attached to the CM in sector D.

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FS-171: For the harnessed-mains architectural option, when the three harness legs deploy, the torque limiter would ride up to its functional height, restrained from going higher by restraining cords. The section of the three harness legs between the confluence fitting (on top) and the torque limiter (on bottom) would be allowed to twist up and untwist, depending on the commands from the RCS. According to information communicated at the December 2008 IDR, this distance would be nominally 6 ft. This would be the effective length of harness that would be allowed to twist up in response to RCS commands.

EO-54: The remaining harness leg lengths from the torque limiter to the CM attach points would be nominally 10 feet each.

FS-172: The torque limiter system includes restraining cords that are nominally 20 feet long (twice the length of remaining harness leg lengths), and are intended to assure that after deployment, the three harness legs lengths from the torque limiter to the CM attach points would all be the same length.

FS-173: The torque limiter system includes securing ties to hold three harness legs in a “triangle” arrangement while deployed.

EO-55: Failure of restraining cords and securing ties are possible during deployment, from contact (dragging across, sliding along or striking against) with CEV structure.

FS-174: Failure of two torque limiter restraining cords is necessary for one harness leg remaining length to deviate from nominal. This feature provides redundancy against loss of intended function.


FS-175: Failure of one torque limiter securing tie could allow one harness leg to become unseated from its place in the torque limiter, if the assembly is twisted. This feature has no redundancy against loss of intended function.

EO-56: The team was unaware of systems that included hardware similar in function to the described rotation torque limiter.

FS-176: The ICD drawing of the rotation torque limiter showed a version that was sized with recesses in which tapes would seat that are two inches wide including a 0.25 inch radius on each side, and with a harness installation clearance of 1.063 inches. This design appears to accommodate three tapes (harness legs or riser) with a maximum size of two-inch wide by one-inch thick. The drawing also showed hole provisions for routing securing ties across the inner surfaces of all three tapes. It also showed hole provisions for routing restraining cords. Various versions of the torque limiter could be manufactured.

EO-57: Installation of Kevlar® tapes (harness legs or risers) would allow a space between the inner surface corners of adjacent tapes, in the untwisted condition. This space would close as twists are added. The number of twists at which the spaces close to zero will be a function of the width and thickness of the tapes, and the dimensions of the torque limiter.



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FS-177: In the single-point attach architectural option, the stowage location for the torque limiter was not specified.

EO-58: In the single-point attach architectural option, the restraining cord feature cannot maintain the torque limiter at its intended height for proper function. When the three risers deploy, the torque limiter would have to “be” at its functional height.

EO-59: Assuming the upper limiter would be retained at its functional height by another method, the section of the three risers between the upper limiter and the lower limiter (at the gusset) would be allowed to twist up and untwist, depending on the commands from the RCS. This distance was not found in information reviewed by the NESC team, but is probably 6 ft by similarity with the other architectural option.

FS-178: If CPAS utilizes a set of two rotation torque limiters for the single-point attach architectural option, with a lower torque limiter integrated into a CM gusset, and a flying upper torque limiter, deployment of the upper torque limiter may contact (strike against) CEV structure as it is extracted from its stowed location. Riser routing may limit the location of a stowage box for the upper torque limiter to sectors A or F, the two sectors that are adjacent to the 0° gusset. These two sectors contain the drogue mortars, one in each.

EO-60: In the single-point attach architectural option, if a main riser fails, the failure of a second riser may not be an independent event, given the confluence and arrangement of the three risers passing through the rotation torque limiter. One slack Kevlar® tape may bind or interfere with the two remaining taut tapes still under tension, causing their unexpected shifting in the torque limiter, and consequently damaging a second tape.


EO-61: In the harnessed-mains architectural option, if a main harness leg fails, the failure of a second harness leg may not be an independent event, given the confluence and arrangement of the three harness legs passing through the rotation torque limiter. One slack Kevlar® tape may bind or interfere with the two remaining tapes still under tension, causing their unexpected shifting in the torque limiter, and consequently damaging a second tape.

## Stowage Container

EO-62: In the harnessed-mains architectural option, there are risks of disorderly extraction of the contents of the stowage container installed in sector D. The container contents (confluence fitting, torque limiter, harness legs), could be damaged by contact (drag across, slide along or strike against) with the CM structure. The container contents could be hindered or prevented from being deployed.

EO-63: In the single-point attach architectural option, the rotation torque limiter may be stowed in a container in Sector A or Sector F (the sectors nearest the 0° Gusset attach location), or may be stowed in a forward bay location without a container. If stowed in a container, there is a risk



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that the torque limiter could be hindered or prevented from being deployed. Whether stowed in a container or not, there is a risk of the torque limiter contacting CM structure.

EO-64: Failure of the torque limiter will prevent CEV roll control prior to splashdown.

## Drogue Mortars

FS-179: All of the CPAS architectural options have two drogue mortars - one each, in sectors A and F of the CM forward bay.

FS-180: The mortars will be provided to Airborne by a subcontractor.

FS-181: An ICD drawing provided showed the mortars to be 1.13 ft diameter with 1.58 cubic ft of volume. (depth 1.4 ft)

FS-182: The mortars have two initiators and two bridge wires, providing redundancy.

FS-183: The mortars are attached to the FBC and remain with the FBC after FBC/CM separation.

FS-184: Apollo conducted tests to characterize mortar propellant degradation with age, and with exposure to full mission environmental conditions including thermal cycles.

FS-185: The CPAS project explained at a February 2009 teleconference that they also would conduct tests to characterize mortar propellant degradation with age, and with exposure to thermal cycles.

FS-186: Packing the confluence ring inside the drogue mortar, on top of the riser and drogue parachute, complicates successful expulsion of the contents of the mortar.


EO-64b: Packing the confluence ring inside the drogue mortar, on top of the riser and drogue parachute might result in more controlled motion of the ring during deployment.

FS-187: Apollo coiled their (steel) drogue risers and encased them in foam disk to improve reliability of expulsion from mortar, eliminating the possibility of developing kinks in the cables.

FS-188: The project calculates the drogue pack density to include the confluence ring mass. This is unnecessarily conservatively and misrepresents the risk of damage to drogue structural components from high density packing.

FS-189: According to information discussed at a March 2009 ERB, the project recognizes the risks associated with a mortar having insufficient energy to eject all of its contents from the mortar with sufficient velocity to inject the drogue d-bag ("last out") far enough into the air stream to begin inflating.

FS-190: Vehicle attitude relative to direction of travel and wind direction can introduce an additional hindrance to successful extraction of drogue mortar contents.

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EO-65: A weak-fired mortar poses a risk of a failure to fully extract a drogue d-bag from the mortar tube, leaving its confluence ring potentially impacting against the side of the CM, or worse, becoming an entanglement hazard for other CPAS components as they deploy from adjacent sectors.

EO-66: There may be risk of a metallic confluence ring contacting the mortar tube's edge on its way out, causing surface damage that subsequently damages a d-bag during its exit.

## Apportionment of Parachute System Components in the Forward Bay Sectors

FS-191: Parachute growth capacity is limited due to confined space.


FS-192: The Apollo design stowed a variety of landing and retrieval hardware and equipment in the four sectors of its forward bay, including but not limited to:

- three main parachute d-bags each with a canopy, suspension lines, and some lengths of a riser inside
- various lengths of three main parachute risers outside the d-bags
- three main parachute pilot chute mortars
- two drogue parachute mortars each with a sabot, a d-bag, a canopy, suspension lines, and some lengths of a riser inside; the riser was coiled and encased in a foam disc.
- two equal lengths of two drogue parachute risers outside the mortars
- a so-called 'flower-pot' parachute fitting attached to the CM between two gussets (45° and 315° with 0° being the 'crew heads up' direction) where drogue and main parachute riser loads were transferred to the CM structure
- CM uprighting system
- Antennas and location aids

FS-193: The CEV design architectures under consideration by the project between December 2008 and March 2009 each also allocated stowage for a variety of hardware and equipment in the six sectors of its forward bay. Assuming the dual drogue harness architectural option, and excluding retention hardware, these stowed items include but are not limited to:

Three-leg-harness main parachute CPAS architectural option


- three main parachute d-bags each with a canopy, suspension lines, and some lengths of a riser inside
- various lengths of three main parachute risers outside the d-bags

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- one metallic main parachute rotation torque limiter
- one metallic main parachute confluence fitting
- two 19-ft harness legs, and one 16-ft harness leg
- one large stowage container for rotation torque limiter, confluence fitting, and excess riser and harness legs
- (no main parachute pilot chute mortars for either architectural option)
- two drogue parachute mortars each with a sabot, a d-bag, a canopy, suspension lines, and some lengths of a riser inside, plus a metallic confluence ring and a short length of one harness leg
- (remaining lengths of drogue parachute harness legs are routed from the mortar tubes outside the FBC, and stowed outside on top of the FBC)
- three main parachute attach fittings attached to the CM at the lower extremity of three of the six gussets (0°, 120°, 240° with 0° being the ‘crew heads up’ direction)
- three pilot parachute packs and extraction lines – if pilot-deployed-mains architectural option
- CM uprighting system (presumed)
- Antennas and location aids (presumed)

Single-point-attach main parachute CPAS architectural option

- three main parachute d-bags each with a canopy, suspension lines, and some lengths of a riser inside
- various lengths of three main parachute risers outside the d-bags
- one metallic main parachute rotation torque limiter
- one smaller stowage container for rotation torque limiter and excess riser lengths
- (no main parachute pilot chute mortars for either architectural option)
- two drogue parachute mortars each with a sabot, a d-bag, a canopy, suspension lines, and some lengths of a riser inside, plus a metallic confluence ring and a short length of one harness leg
- (remaining lengths of drogue parachute harness legs are routed from the mortar tubes outside the FBC, and stowed outside on top of the FBC)

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- a second metallic rotation torque limiter, integrated halfway up the CM's 0° gusset ('crew heads up' direction), three main risers pass through one hole, the three belt-cross section risers making a 120° angle with each other.
- three main parachute attach fittings integrated into the CM's 0° gusset, at three places beneath the gusset-pass-through location.
- three pilot parachute packs and extraction lines – if pilot-deployed-mains architectural option
- CM uprighting system (presumed)
- Antennas and location aids (presumed)

FS-194: Apollo used approximately 75% of the available volume of its forward bay – three of four sectors (each sector defined by a pair of gussets) – as stowage volumes for three main parachutes. Each of these three volumes also contained one main pilot parachute mortar and one CM uprighting bag. The fourth sector in the Apollo design contained two drogue mortars, one flower-pot attach fitting, and much of all the remaining hardware stowed in the forward bay.


FS-195: As reviewed between December 2008 and March 2009, the Orion CEV allocates 50% of the available volume of its forward bay – three of six sectors defined by pairs of gussets – as stowage bays for three main parachutes.

FS-196: Assuming all things are scaleable, the CPAS Project is being asked to achieve a 33% reduction in the stowed volume of its main parachutes – from 75% of available volume to 50% of available volume.

EO-67: Advances in parachute design and materials technology since the development of the Apollo ELS could possibly achieve a 33% reduction in required volume for the parachute packs (proportionally compared to Apollo), but if not, an overaggressive reduction may introduce new reliability risks for CPAS that may adversely affect the overall probability of LOC.

FS-197: Apollo used portions of its remaining sector for stowage space for short lengths of drogue risers, short lengths of main risers and two drogue mortars, of which the latter used the majority, proportionally. Apollo mortar sizes were increased during vehicle development due to CM weight increases and subsequent increases in drogue parachutes.

FS-198: CPAS has been allocated portions of the CEV's remaining three (of six) sectors in its forward bay, for stowage space for main harness legs, medium lengths of main risers, a confluence fitting, a torque limiter, a storage box, and two drogue mortars. In some architectural options under consideration by the project between December 2008 and March 2009, the harness legs and confluence fitting has been deleted.

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EO-68: Orion CEV might have a requirement that demands more of the available volume of the forward bay (proportionally compared to Apollo), for hardware that is not related to CPAS. If this is true, then if these systems are not related to crew survival, design trades between these items and CPAS components should not be made if they introduce new reliability risks for CPAS that may adversely affect the overall probability of LOC.


EO-69: Using four of six sectors on the CEV forward bay for four main parachutes would provide 66% of the available volume for packed parachutes. Assuming all things are scaleable, this would provide for at least a 12% improvement based on advances in parachute design and materials technology since the development of the Apollo ELS (from 75% of available volume to 66% of available volume).

EO-70: A CPAS architecture with four main parachutes instead of three, could introduce new reliability risks for CPAS that may adversely affect the overall probability of LOC. Technical assessment is necessary to establish the merits and demerits of such an architecture.

EO-71: One architectural option that addresses many of the NESC team's recommendations comprehensively would include:

- Four main parachutes in four d-bags stowed in sectors B, C, D, and E, that could be smaller, less dense, and possess volume reserve.
- Total 4-pack volume that could be 20% greater than the assessed 3-pack total volume, representing 60% of total forward bay volume, rather than 50%.
- This would be achieved with a 5% growth in total parachute mass, a 5% decrease in the size of each pack, a 5% decrease in pack density, and still retain a 5% volume reserve going into PDR.
- One failed main would represent 75% capability rather than 66% capability.
- Smaller main pack shapes can be simplified, possibly avoiding wrapping around the LAS Wells.
- Redundant Kicker straps.
- Single point attach at Gusset 0. Gusset assessed as DFMR.
- One DFMR steel riser, one DFMR confluence fitting, and four fabric risers.
- No torque limiter. The steel riser will twist-up to minimize rotation torque, between the gusset attach and the confluence fitting.

## Project Technical Requirements Specification (PTRS)

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FS-199: A preliminary draft of CPAS Requirements (Project Technical Requirements Specification, PTRS) was published in October, 2008, and provided to the NESC team at the IDR in December 2008.

FS-200: The PTRS and an associated document called the “Assumptions document” got final signatures in January 2009 (double check), and both were provided to the NESC team.

FS-201: Significant changes were made to the PTRS and assumptions documents between December 2008 and March 2009.

FS-202: The initial conditions for drogue mortar firing defined in the PTRS for CPAS are incomplete.

FS-203: Appropriate and validated parachute analysis tools will be critical to the design of CPAS and the verification of requirements.

FS-204: [I.CPAS.CM.006] CPAS shall limit the vertical descent rate of the CM to less than 10.07 m/s (33.0 ft/s) at standard sea-level conditions (as defined in NASA-TM-X-74335, U.S. Standard Atmosphere, 1976) for a maximum CM mass of 9,464.2 kg (20,865.0 lbm). (PTRS, October 2008)

FS-205: It will be difficult to statistically verify requirement since it is written in absolute terms. [I.CPAS.CM.006].

FS-206: [R.CPAS.018] CPAS shall meet all functional and performance requirements of this specification when subject to one drogue parachute and one main parachute failure. Rationale: This requirement refers to a complete loss of one drogue and one main parachute on the same landing event. Each subcomponent of CPAS (drogues and mains) should be one fault tolerant. (PTRS, October 2008)


FS-207: Requirement [R.CPAS.018] does not explicitly include the possibility that one drogue parachute will fail without the subsequent failure of one main parachute.

FS-208: [I.CPAS.CM.011] CPAS shall limit the peak total parachute load (3-sigma) to less than the peak loads defined in Table 3.3-1, Parachute Peak Loads, under all fault conditions defined in [R.CPAS.018], [R.CPAS.017], and [R.CPAS.129]. Rationale: These peak loads define the extreme load to which the CM design will be based. While the CPAS is not required to design the parachutes to survive the skipped reefing stages defined in [R.CPAS.018], these failures must not impart more load into the CM and load-carrying structures than listed here to prevent the failure from propagating into a catastrophic failure. (PTRS, October 2008)

FS-209: Requirement [I.CPAS.CM.011] does not specify a limit peak parachute load under the (most likely) nominal condition where there is no fault in the system.

FS-210: Requirement [I.CPAS.CM.011] does not limit the direction in which the parachute peak loads are applied.



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FS-211: [R.CPAS.012] CPAS shall design to meet or exceed the load dispersions for each fault case defined in Table 3.3-2, Parachute Load Dispersions. Rationale: Load dispersions result from Monte Carlo analyses which vary performance parameters. Designing for 3-sigma dispersions in low likelihood cases drives up mass for very little return in overall reliability. For the purposes of this requirement, the analyses will vary all relevant parachute performance parameters (drag area, opening shock, cutter times, etc.), and all initial conditions defined in [R.CPAS.005], [I.CPAS.CM.128], [I.CPAS.CM.129], [I.CPAS.CM.132], [I.CPAS.CM.133], [I.CPAS.CM.134], [I.CPAS.CM.135] and [I.CPAS.CM.139]. The analyses results assume the use of 3 main and 2 drogue parachutes in the CPAS configuration. Trajectory conditions will be assumed at the edges of the deploy trajectory envelope defined in [R.CPAS.005] and use NASA-TM-X-74335, U.S. Standard Atmosphere, 1976. (PTRS, October 2008)

FS-212: Requirements [R.CPAS.012] is silent on whether the parachute that had a skipped reefed stage remains operational or not.

F-213: Using multiples of “sigma” in specifying requirement [R.CPAS.012] may yield an unacceptable percentile of cases that exceed the specified loads since this percentile depends not just on “sigma,” but also in the probability distribution, which is not known up front.

FS-214: PTRS fig 3.1-1 is not clear whether “roll rate” refers to wind or body axis. (PTRS, October 2008)

FS-215: Project is using Monte Carlo dispersions generated by DSS simulations to set the Requirement for CEV attitude at drogue deployment at +/- 70°.

## Analysis, General


EO-72: Appropriate and validated parachute analysis tools will be critical to the design of CPAS and the verification of requirements.

FS-216: A tool called Decelerator Dynamics (DCLDYN) is an in-house FORTRAN analysis tool used by Airborne for two-body dynamic analysis of a parachute and an item of cargo suspended beneath the parachute. The two simulated bodies are connected by a nonlinear spring representing the riser, the suspension lines, and the canopy’s radials. Each body is modeled with 3 DOF: vertical (along the axis between the two bodies), horizontal (perpendicular to that axis), and pitch. Roll and yaw cannot be analyzed.

FS-217: DCLDYN models represent other parachute-specific features, such as drag and mass as a function of time; disreefing schedules; parachute opening parameters; parachute shape and time parameters.

EO-73: DCLDYN appears to be the Design Team’s principal analysis tool.



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FS-218: It is not clear how DCLDYN has been validated for use to compute numbers that are used to justify significant design decisions.

FS-219: Design Team analysts use DCLDYN to account for a phenomenon wherein a percentage of parachute mass reaccelerates towards the cargo velocity at line stretch.

FS-220: DCLDYN analysis accounts for apparent mass effects wherein a parachute mass increases during inflation, as the mass of air ‘inside’ it increases.

FS-221: DCLDYN cannot model a cluster of multiple parachutes. Spreadsheet simulations are constructed to model multiple parachutes. The spreadsheet simulations do not include a nonlinear spring parameter to represent the riser/lines/radials. Ratios determined from the spreadsheet simulation are used in a subsequent DCLDYN simulations.

FS-222: During a teleconference with the NESC team in February 2009, the project lead indicated an intention to run a NASA analysis tool, Dynamic System Simulator (DSS) for checks of DCLDYN.

FS-223: DSS is a NASA high-fidelity code that can be used for dynamic analysis of parachutes and items of cargo.

FS-224: A review of Gen-1 test reports revealed that DCLDYN mispredicted opening load and inflation time of the pilots, drogues, and mains.

FS-225: A review of Gen-1 test reports revealed that results from both DCLDYN and DSS were used by the project but no direct comparison of DSS and DCLDYN results were ever shown. Results from one analysis tool were always presented independently from the other.


FS-226: A review of Gen-1 test reports revealed that a migration by the Design team from using predominantly DCLDYN in CY 2007, and increased use of both DCLDYN and DSS in CY 2008.

FS-227: During a teleconference with the NESC team in February 2009, the project indicated an intention to run a less-detailed analysis tool known as OSIRIS for verification analysis and requirements closure. (Integrated GNC Design and Data book, Section 9.1.4.)

FS-228: POST is a generalized point mass, discrete parameter targeting and optimization program that provides the capability to target and optimize point mass trajectories for multiple powered or unpowered vehicles near an arbitrary rotating, oblate planet. POST is supported by NASA LaRC.

EO-74: Using two different codes, such as DCLDYN and DSS or POST and DSS, has in previous projects resulted in revelation of shortcomings of each code, and improved confidence in results.

## Analysis, Specific Issues

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EO-75: Validation, verification, and/or calibration are planned by CPAS to support uncertainty estimates on results that feed into the reliability estimates.

FS-229: LS-DYNA is an advanced general-purpose multiphysics simulation software package that is actively developed by the Livermore Software Technology Corporation (LSTC).

FS-230: The project has used LS-DYNA to determine preliminary Kevlar® harness hysteresis curves, to establish the appropriate main harness leg lengths that would provide the required hang angle at landing.

FS-231: According to charts prepared for a brief by CPAS to a Lockheed Engineering Review Board in March 2009, the project intends to use LS-DYNA for simulation of separation of the FBC from the CM.

FS-232: Project analysts have run Monte Carlo analyses with DCLDYN for stochastic nondeterministic problems.

FS-233: Results from DCLDYN Monte Carlo analyses of drogue parachute loads were presented at the December 2008 IDR. Results represented all seven points of the deployment envelope, and included analyses of an aggressive disreefing schedule for deployment after pad abort.


FS-234: Results from DCLDYN Monte Carlo analyses of drogue parachute loads presented at the December 2008 IDR indicated that input dispersion for the analysis included 5 parameters for the CM, and between 16 and 19 parameters for a parachute that was modeled to represent two drogue parachutes as one.

FS-235: The DCLDYN Monte Carlo analyses of drogue parachute loads presented at the December 2008 IDR showed all input dispersions were based on Gen-1 data.

FS-236: The DCLDYN Monte Carlo analyses of drogue parachute loads presented at the December 2008 IDR used uniform dispersions for all parameters. Presented charts indicated a plan to review the distribution types for future analyses.

FS-237: The CPAS IDR charts showed the Monte Carlo analysis used uniform dispersions for the dispersed parameters. Design requirements state analysis will show CPAS performance to meet the requirements to a specified sigma value, assuming normal distributions. Monte Carlo results using uniform dispersions will likely not fit a normal distribution well, given the parameter space shown in the IDR.

FS-238: The CPAS IDR charts showed a mass reduction for not having the skipped reefing stage requirement. There was no skipped reefing stage requirement for Apollo. To protect for this, extra reefing lines and cutters were incorporated into the design. These extra reefing lines were however required to meet Apollo reliability requirements (pg 23, “The Apollo Parachute Landing System,” Knacke).

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FS-239: There are only 2 simulations apparently being used in making design decisions, DCLDYN and DSS. The 2 simulations are working closely and not independently.

FS-240: System definitions and data are provided across a broad range of documents. Configuration documents have been found in PDF, Word, and PowerPoint format. Some of the documents contradict each other (dispersions).

FS-241: DCLDYN Monte Carlo analyses were also run to assess drogue and main riser loads sensitivities to other parameters.

FS-242: Limit load requirement for drogues is 55,000 lb (either or both drogues).

FS-243: Results from DCLDYN Monte Carlo analyses of main parachute loads presented at the December 2008 IDR indicated that some design load requirements were exceeded for that preliminary look.

FS-244: Peak drogue riser load at initial opening to 1<sup>st</sup> stage, was found to be most sensitive to

- Initial pitch angle of vehicle
- 1<sup>st</sup> stage reefing ratio
- 1<sup>st</sup> stage fill constant
- 1<sup>st</sup> stage Ck

FS-245: Peak drogue riser load at disreef from 1<sup>st</sup> stage to 2<sup>nd</sup> stage, was found to be most sensitive to

- 2<sup>nd</sup> stage reefing ratio
- 2<sup>nd</sup> stage Ck
- 1<sup>st</sup> stage reefing ratio

FS-246: Peak drogue riser load at disreef from 2<sup>nd</sup> stage to full open, was found to be most sensitive to


- 3<sup>rd</sup> stage Ck
- 2<sup>nd</sup> stage reefing ratio

FS-247: Peak main riser load at initial opening to 1<sup>st</sup> stage, was found to be most sensitive to

- 1st stage fill constant


FS-248: Peak main riser load at disreef from 1st stage to 2nd stage, was found to be most sensitive to

- 2nd stage reefing ratio

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FS-249: Peak main riser load disreef from 2nd stage to full open, was found to be most sensitive to

- 2nd stage reefing ratio

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## Testing, General

FS-50: Prior to October 2008, Airborne performed demonstration testing of various elements of a “Generation 1” parachute system to develop data that was expected to have utility for CPAS development.

FS-251: The system architecture briefed in December 2008, is so-called ‘Generation-2,’ differed in significant ways from the Generation-1 architecture.

FS-252: Some Gen-1 test data is applicable to the Generation-2 system.

EO-76: A great deal of developmental ground and flight testing will be necessary to qualify any of the CPAS architectural options that were reviewed by the NESC Team between December 2008 and March 2009.

EO-77: Testing conducted by the project between December 2008 and March 2009, appeared to lack a methodological approach.

EO-78: Testing conducted between December 2008 and March 2009 appeared to be principally for the means of evaluating design concepts.

FS-253: No Gen-2 verification and validation testing was accomplished between December 2008 and March 2009.

FS-254: Between December 2008 and March 2009, a test matrix was not available for the NESC team to review.

FS-255: The project’s draft V&V Plan will not be available until near PDR.


EO-79: All testing conducted, including development, should be done in support of the design effort, building confidence in the design, and eventually qualification.

EO-80: The Verification and Validation matrix should address all requirements set forth in the ICD and the PTRS.

EO-81: The project has not clearly identified what is required to pass through the gate of PDR.

EO-82: Given the broad range of initial/boundary conditions on the CPAS performance envelope for the CPAS and the expense of testing, the final certification of CPAS is likely be highly dependent upon modeling and simulation results. Modeling and simulation results are only valid after the model(s) is(are) thoroughly understood, the application limits have been established, have been deemed valid for use in the application, and have been verified by test data and/or comparison to other models and we have heard very little of any plans for such a V&V program. A rigorous review process must be applied for the validation and verification test program used to certify a modeling based approach.

FS-256: Revision of PTRS in March 2009 changed the following:

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- An update to the CPAS drogue deploy envelope was made.
- The pad abort, main parachute deployment initiation requirement was deleted.
- The CM hang angle requirement was deleted.
- Requirements were reworded to be better defined.
- Drogue parachute pack mass was stipulated to be 31.5 kg (69.5 lbm).
- Operational temperature bounds were changed from -54 C (-65 F) to -83 C (-117 F).
- The gaseous methane and oxygen requirements were deleted.
- Main and drogue parachute failure tolerance requirements were revised for nominal entry and pad aborts.

## Testing, Specific Issues

EO-83: The Apollo Experience Report – Earth Landing System (ELS), NASA TN D-7437, (1973), illustrates the extent of the testing that was necessary to demonstrate the overall reliability of the ELS system, to make it suitable for manned flight. It also illustrated the need for thorough systems integration and compatibility verification.

FS-257: The Apollo Experience Report – ELS does not contain data useful for creating reliability estimates.

FS-258: Some quantitative Apollo data useful for creating reliability estimates is in the Knacke Book.


FS-259: The Northrop Venture report 4040, Apollo Earth Landing System, report of reliability Analysis (1968) could not be located by individuals at Northrop who are contracted with the NESC for other purposes.

FS-260: Developmental test data from Apollo Earth Landing System that might be useful to CPAS reliability assessments is not readily available.

FS-261: The Gen-1 forward bay full-scale mockup shown in pictures in IDR charts lacks significant geometric details including LAS Wells, integrally machined features on the tunnel, and features on the gussets.

FS-262: The project's first draft Test Matrix is not expected until after March 2009.

FS-263: the project's first draft Verification and Validation plan is not expected until closer to the project's PDR (NLT September 2009.)

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FS-264: According to a chart presented by the S&MA Team in February 2009, a draft plan for methods to generate reliability data included the following:


Function	Method
Main / Drogue Confluence Fitting	Cluster Test
Environment Induced Failure	Historical / Test
Rigging Error (Main + Drogue)	Historical Data
Far-Field Contact	Auxiliary Test
Near-Field Contact	Ground Testing
Main Chute Entanglement	Flight Testing
Drogue / Auxiliary Entanglement	Flight Testing
Skipped Reefing Stage Failure	Historical Data
Chute Deployment Failure	
Friction Failure Due to Rapid Extraction	Historical / Test
Disorderly Deployment	Historical Data
Inadvertent Chute Release	Integrated
Bag Cutter Failure	NSI + Integrated
Single Chute Near-Field Contact	Ground Testing
Inflation Failure	Historical Data
Failure Due to Extraction Line Load Too High	Unknown

FS-265: The table indicates that the project recognizes that for the dual drogue confluence fitting architectural option, cluster testing is necessary to verify and validate load sharing assumptions and to generate data of the probability of damage to one or both confluence rings during deployment.

EO-84: There is risk of damage to one or both drogue confluence rings between deployment from drogue mortars and line stretch from:

- Impact with the mortar while exiting the tube
- Impact with the mortar cover during or after exiting the tube
- Impact with each other
- Impact with FBC structure
- Impact with CEV structure



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FS-266: The table indicates that the project recognizes that for the harnessed-mains architectural option, cluster testing of the main confluence fitting is necessary to validate load sharing assumptions.

FS-267: The table indicates that the project recognizes that environmental laboratory testing is necessary where test data does not already exist.

FS-268: The table indicates that the project recognizes that historical data is necessary to estimate the probability of failure of main or drogue inflation due to errant rigging.

FS-269: The table indicates that the project recognizes that testing is necessary to verify and validate the reliability of the auxiliary chute system which is intended to decelerate the FBC after release, so as to reduce the risk of its subsequent interference with one or more inflated main parachutes, main suspension lines, main risers, or main harness.

FS-270: The Apollo Block II ELS forward heat shield (FHS) incorporated a 7.2 ft auxiliary chute, the same one used as pilot parachutes for main chute deployment. The auxiliary chute's mortar was redesigned to fit in the available volume that was inside the heat shield adjacent to the top of the tunnel.

FS-271: The Apollo Block II ELS aux chute mortar was initiated by a time-delayed distance-switch on a short lanyard that pulled tight during cover separation as the cover cleared the tunnel.


FS-272: The Apollo Block II ELS auxiliary chute was deployed laterally compared to the vehicle flight path, through the opening above the tunnel as the CM dropped from the FHS. Inflation of the chute exerted a force that redirected the cover into a separate flight path and subsequently slowed the rate of descent of the FHS and took it out of the wake and flight path of the Command Module.

EO-85: The Apollo Project recognized that premature firing of the Apollo auxiliary chute could have resulted in an inability to jettison the FHS. Extensive testing verified that the Apollo auxiliary chute reliability was sufficient so that its benefits would outweigh its risks.

FS-273: Comprehensive testing with a boilerplate vehicle was used to verify and validate the reliability of the Apollo Block II ELS auxiliary chute system because contact of the forward heat cover that damages more than one main parachute, main suspension lines, main risers, or main harness, was recognized to result in LOC.

FS-274: The CPAS auxiliary chutes being considered by the project are two 10 lb. ring sails, nominally 25.7 ft diameter. For comparison, the two drogue parachutes are nominally 23 ft in diameter.

FS-275: The CPAS auxiliary chutes are installed beneath the drogue mortars and fired by a gun simultaneously towards one side of the FBC.

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EO-86: A preliminary assessment of the CPAS auxiliary chute architectural option suggests that the concept of operation is principally to provide additional drag to decelerate the FBC after release. Suspended beneath two drogue parachutes, the force from two auxiliary parachutes inflating off to one side, at low speed, may not significantly redirect the FBC laterally out of the vehicle flight path. Their chief benefit would be to decelerate the FBC relative to the CM.

EO-87: The FBC will decelerate rapidly after releasing the CM.

FS-276: According to information in the IDR charts, the terminal  $q$  of the FBC suspended by two inflated drogues is 1.26 psf.

EO-88: As discussed in a CPAS Project teleconference in March 2009, the project appears to discount the risk of damage to more than one main risers from contact by an FBC that is suspended on only two parachutes (any combination of drogue and auxiliary chutes) and is falling faster than the suspended CM. The Project rationale is that that risers will be relatively lightly loaded at impact.

FS-277: PTRS 3.2.4.3 requires prevention of propagation of component failures that can result in catastrophic hazard.

FS-278: The table indicates that the project recognizes that ground testing is necessary to verify and validate that main d-bags will not suffer damage from contact with CEV structure or FBC structure, as they are lifted from their stowed locations.


FS-279: The table indicates that the project recognizes that ground testing is necessary to verify and validate that main risers will not suffer damage from contact with CEV structure or FBC structure, as they are deployed from their d-bags. It is not clear if the project recognizes this should be system-level ground testing with a geometrically accurate CM mockup.

FS-280: The table indicates that the project recognizes that ground testing is necessary to verify and validate that main canopies and suspension lines will not suffer damage from contact with FBC structure, as they are deployed from their d-bags.

FS-281: The table indicates that the project recognizes that ground testing is necessary to verify and validate that for the loosely-attached mains architectural option and loosely-attached pilots architectural option, components that attach same to the FBC will not suffer damage from contact with FBC structure, as contents are deployed from the d-bags.

FS-282: The table indicates that the project recognizes that flight testing is necessary to develop data needed to estimate the risk of main chute entanglement, regardless of main deployment architectural option.

FS-283: The table indicates that the project recognizes that aerial drop flight testing is necessary to develop data needed to estimate the risk of entanglement between drogue parachutes and auxiliary parachutes.

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FS-284: The table indicates that the project recognizes that historical data is available to estimate the risk of skipped reefing stage failure.

FS-285: The table indicates that the project recognizes that the risk of chute deployment failure due to burn damage from rapid extraction cannot be solely characterized with historical data, and that incorporation of new materials or novel applications of materials, and high packing density all compel extraction tests.

FS-286: For the loosely-attached mains architectural option, the extraction of a main d-bag from its stowage sector can be hindered by contact (drag across, slide along or strike against) with CM structure. Hindrance of extraction can be followed by a more rapid extraction than nominal. This can lead to subsequently more rapid extraction of the contents from the d-bag (riser, suspension lines, canopy). This rapid deployment can generate heat from friction that can damage Nylon, Kevlar<sup>®</sup>, and Vectran fabric materials. Vectran offers less strength retention at high temperatures than Kevlar<sup>®</sup>.

FS-287: The table indicates that the project recognizes that historical data exists to characterize the risk of failure due to disorderly deployment.

FS-288: The table indicates that the project recognizes that premature release of a chute is an integrated risk, but does not specify how the risk will be established.

FS-289: The table indicates that the project recognizes that the risk of a bag cutter failure can be characterized by available NSI data.


FS-290: The table indicates that the project recognizes that inflation failure can be characterized with historical data.

FS-291: The project recognizes a risk with the loosely-attached mains architectural configuration, of snatch loads on the main d-bags handles being high, which can lead to a physical failure which results in leaving a d-bag in its stowage location. Mitigations discussed by the project included the addition of energy modulators on the bag handles.

FS-292: In December 2008 and February 2009 versions of the IDR charts, the main risers were indicated to be 1.75 inch wide Kevlar<sup>®</sup> Tape with 8 plies.

FS-293: In December 2008 and February 2009 versions of the IDR charts, the main harness legs were indicated to be 1.75-inch wide Kevlar<sup>®</sup> Tape. They were indicated to have 14 plies in December 2008 and 18 plies in February 2009.

FS-294: If a rotation torque limiter is incorporated into the main riser system for either the harness-mains architectural option or the single point attach architectural option, the three involved lengths of Kevlar<sup>®</sup> tape will be allowed to twist so the vehicle's RCS can maintain a CM orientation with the crew's feet towards the horizontal direction of travel prior to landing.

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FS-295: In December 2008, Airborne had manufactured or procured subscale harness legs for testing in a Tinius Olsen tensio-meter (twist fixture). The test legs were said to be quarter-scale, but shown in the image next to a ruler, to be approximately one inch in width.

FS-296: In December 2008, tests were being planned to measure tension in sets of subscale Kevlar<sup>®</sup> Tape, while twisted, to characterize strength degradation with respect to number of full twists, up to five twists. One twist was defined as 360°.

EO-89: Three tapes with rectangular cross sections, held in a torque limiter in a triangular arrangement at a 120° angle to each other (but not touching each other at the ends when untwisted), will touch each other along their lengths at some number of twists that will depend on the lengths and the widths of the tapes. Twisting beyond this point will put stresses on the tapes that will be difficult to predict and could pose a risk of failure. Torque limiter dimensions can be designed to avoid stresses that could damage the tapes, securing ties, or restraining cords.

FS-297: Between December 2008 and March 2009, stretch testing was being planned to apply peak loads to full-scale fabricated Kevlar<sup>®</sup> harness legs, to characterize their hysteresis curves, to verify completed analyses that established that one 16 ft harness leg and two 19 ft harness legs would provide the required hang angle at splashdown.

FS-298: Apex forward deployment of the drogues or the mains is not a requirement.

FS-299: There are numerous opportunities for damage to Kevlar<sup>®</sup> tapes and cords expected to be used for drogue harness legs, risers, suspension lines, and main harness legs, risers and suspension lines, from contact with sharp edges on the CEV and FBC.

FS-300: The project approach to mitigate these risks is to require large radius edges on any protruding or exposed CM or FBC hardware.


FS-301: The separation of the LIDS prior to initiation of the CPAS system may present a sharp edge on the top of the tunnel.

FS-302: An off-nominal LAS separation could result in the LAS contacting the FBC on its way out.

EO-90: During a Hardware IPT in February 2009, it was noted by a participant that steel risers were still carried as a design alternative for CPAS.

FS-303: According to charts prepared for a brief by CPAS to a Lockheed Engineering Review Board in March 2009, high altitude and high Mach tests will be performed with single-drogue drop tests. These will not include cluster tests of two drogues. These will not provide information about wake effects.

EO-91: Cannot drop test parachute test cargos from a C-17 above 20,000 ft.

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FS-304: The unmanned Ares-1Y ascent abort flight test will provide data on CPAS parachute performance at higher altitudes in the drogue deployment envelope.

## Testing, Drogues Development

FS-305: CPAS employs 2 Drogue Parachutes, only 1 of the Drogues is required to establish Main Parachute deployment conditions

FS-306: Airborne IDR chart said that the drogues to be used for flight test development unit (FDU) will have two-inch wide 2000 lb Nylon ripstops added to the trailing edge tapes of the vent, the upper shoulder, and the lower shoulder.

FS-307: Apollo drogues deployed with risers out of tube first, encased in a foam disk, then the packs, with the d-bag mouth facing outwards.


FS-308: The two Apollo drogues fired at an included angle of approximately 60 degrees. The kick load on the Apollo CM would tend push the vehicle apex away from direction of deployment of the two drogues, regardless of the vehicle's initial attitude. From each tube, the steel riser came out first, encased in a foam disk, and uncoiled from its foam encasement. The suspension lines played out of the d-bag as the pack turned around, and the canopy came out of the d-bag last. ELS system designers assumed that the vehicle could be in any attitude at drogue line stretch. Each drogue's line stretch load would tend to pull the CM apex towards the direction of line stretch.

EO-92: The Orion CEV has two three-legged drogue harnesses and two confluence rings. The rings are stowed one in each mortar. The included angle between the two mortars is not known to the NESC team. Similar to the Apollo system, the kick load on the Orion CM would tend to push the vehicle apex away from the direction of deployment of the two drogues, regardless of the vehicle's initial attitude. From each tube, the confluence ring comes out first, then the Kevlar<sup>®</sup> tape riser, then the d-bag. When one or both harnesses go into tension (extracted from their stowed location on top of the FBC), the event would tend to pull the apex towards the direction of deployment. The suspension lines would play out of the d-bag as the pack turned around, and then the canopy would came out of the d-bag last. Each drogue's line stretch load would tend to pull the CM apex towards the direction of line stretch. The vehicle could be in any attitude at drogue line stretch.

FS-309: The project estimated a failure of 1:333 for "drogue bag separation."

EO-93: The 1:333 estimate for "drogue bag separation" failure likely refers to a d-bag not getting propelled far enough out to catch the free stream airflow, due to insufficient energy of the mortar.

FS-310: Airborne chart said - Drogues are completely independent. Failure of one drogue due to skipped reefing will not affect the other drogue.

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FS-311: No FBC design detail has been made available about the drogue attach fittings. For the single confluence fitting architectural option, there will be one attach bolt per fitting at 60°, 180°, and 300°, near the top of the FBC. (crew 'heads up' is 0°). For the dual drogue confluence fitting architectural option, there will be two attach bolts per each fitting at the same three locations. The fittings will have to be protected by TPS.

FS-312: No FBC design detail has been made available about the load path through the FBC from drogue harness fittings to the FBC attachment to the CM. The three FBC release mechanisms are integrated into CM forward bay gussets at the same three locations (60°, 180° and 300°), to react drogue harness leg loads.

## Testing, Mains Development

FS-313: CPAS employs 3 Main Parachutes, only 2 of the 3 Mains is required to establish the terminal descent conditions for a safe landing

FS-314: Apollo system mains were mortar-deployed in 3 directions, 120 degrees apart, within a plane. If all 3 mortars fired simultaneously, the net kick load on the vehicle at mortar fire would be zero. If all 3 pilot parachutes pulled all 3 mains out synchronously and all 3 main parachutes reached line stretch simultaneously, the net force on the vehicle at line stretch would be zero.

FS-315: Intentionally blank

FS-316: There is a risk during main parachute deployment of one canopy becoming a leader in initial filling. The leader runs the risk of encountering excessive loads with the initial deceleration loads not being shared amongst the other two.

## Trigger Logic

FS-317: According to Lockheed document CEV-T-078005, reviewed in February 2008, GPS-derived altitude and velocity are used to initiation decent and landing phase events, such as FBC release, drogue deployment, main deployment, depend


FS-318: According to Lockheed document CEV-T-078005, reviewed in February 2008, IMU-propagated altitude is used as a back-up to GPS-derived altitude.

FS-319: IMU propagated altitudes could contain altitude errors on the order of tens of thousands of feet.

FS-320: According to charts prepared for a brief by CPAS to a Lockheed Engineering Review Board in March 2009, CPAS has decided to use IMU-propagated velocity as the trigger for drogue mortar initiation, for ISS reentries.

FS-321: The velocity to which the CEV must slow to during reentry in order to trigger drogue mortar initiation is 676 feet per second (206 meters per second).



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FS-322: Based on project simulations, the target trigger velocity will result in a drogue deployment altitude range of between 45,000 ft down to 32,000 ft.

FS-323: The FBC release is on a timer, 82 seconds after the drogue mortars are initiated.

FS-324: A barometric altimeter option is being considered by the project as a back-up but is not baselined at this time.

FS-325: Apollo used a barometric altitude trigger.

FS-326: The project has not included a manual deployment capability for the initiation of drogue deployment or other stages. The Apollo ELS had manual backup capability.

FS-327: According to charts prepared for a brief by CPAS to a Lockheed Engineering Review Board in March 2009, GPS data will be qualified for use after the vehicle becomes operational, and will be used for reentries from lunar missions.

## Environmental

EO-94: Ascent out-gassing could damage the TPS covering the drogue harnesses on top of the FBC, creating risk to the harnesses during reentry heating.

FS-328: A review of CPAS preliminary design details reveal a risk of heat damage to the drogue harness legs stowed on top of the FBC covered with TPS, during normal reentry, if the TPS has been damaged at any time prior to or during entry insertion. A single fault can damage two drogue legs—one from each parachute per the routing scheme.

FS-329: Textile material properties change with age.

FS-330: Mortar propellant properties change with age.

## Pad Abort

FS-331: The requirement for max terminal rate of descent at landing is 33 fps.

FS-332: The PTRS Para 3.2.1.2.3 “Full deploy at min altitude” assumes no wind for pad abort.


FS-333: The PTRS Para 3.2.1.1.4 requires at most 5 seconds between drogue mortar initiation and the initiation of FBC release for a pad abort. IDR chart 62 says 0 to 5. Discussion later said 2-5.

EO-95: The CM may be unstable at LAS hand-off. The project is performing trades to establish test points.

FS-334: Monte Carlo analyses run in March 2009 show wide attitude and load dispersions for pad abort. (Point 7 on the drogue deploy envelope.)


FS-335: Orion GNC requirements are one failed drogue or one failed main.



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FS-336: CPAS is changing the PTRS to align with GNC requirement – single chute fault tolerant.

EO-96: A failed main may not be an independent event to a failed drogue. Operation with one failed drogue may affect stability which may in turn affect probability of near field contact during FBC separation.

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## **Appendix C.1. Stakeholder Outbrief of Interim NESC Recommendations 2 (September 2009)**

The version of the Stakeholder Outbrief 2 in this Appendix differs slightly from that which was approved by the NRB. Figures included to facilitate board member understanding were removed in the stakeholder package. Also, backup material was added: a sample Functional Verification Matrix and a tutorial, *Introduction to Design of Experiments*. All are included in this Appendix.

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	Michael Kelly
	September 24, 2009

# **Crew Exploration Vehicle (CEV) Parachute Assembly System (CPAS) Independent Reliability Assessment**

## **Stakeholder Outbrief of Interim NESC Recommendations**


Assessment of design development and test planning between  
December 2008–August 2009

**Michael Kelly**  
NESC Principal Engineers Office  
**September 24, 2009**

NESC Request No: TI-08-00487

This briefing is for status only and does not represent complete engineering data analysis

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<h2 style="text-align: center;">Background</h2>	Michael Kelly
	September 24, 2009

### Assessment Objective:


Identify design and/or process improvement opportunities, assess the robustness of the development test plans, and make recommendations that will increase the reliability of CPAS and ensure the success of the integrated system.

### Timeline:

<u>Month</u>	<u>Activity</u>
12/08	Team attended Internal Design Review (IDR) #1
04/09	<b>Team out-briefed <i>Interim</i> NESC Findings (20), Observations (24), and Recommendations(30)</b> <b>—Related to architectural options and design development practices that can impact reliability</b>
05/09	Team attended IDR #2
05/09-07/09	Assessment hiatus
06/09	Orion Subsystem Design Review (SSDR)
06/09	Integrated Design Assessment Team (IDAT) chartered —CPAS, Lockheed and MSL EDL, collaboratively exploring design trade space
07/09	Orion System and Module Review (SMR)
09/09	Team to attend IDR #3
09/09	<b>Team to out-brief <i>Interim</i> NESC Findings (3), Observations (2), and Recommendations (2)</b> <b>—Related to development and verification test planning and Design of Experiments (DOE)</b>
09/09-10/09	IDAT architecture down-selection expected
11/09	Draft CPAS Master Verification Plan expected
11/09	<b>Team to out-brief <i>Final</i> NESC Findings, Observations, and Recommendations</b> <b>—Related to down-selected architecture, test planning and DOE</b>
12/09	<b>Final report complete</b>
03/10	CPAS Preliminary Design Review (PDR)


} Subject to change based on project performance

This briefing is for status only and does not represent complete engineering data analysis

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<h2 style="text-align: center;">Team Listing</h2>	Michael Kelly
	September 24, 2009

Last Name	First Name	Discipline	Organization/Location
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Cruz	Juan	Parachute Systems	NASA, LaRC
Hengel	Jack	Parachute Systems	NASA, MSFC
Huegel	Fred	Electrical/Avionics	NASA, GSFC
Jambulingam	Natesan	Statistics/Reliability	NASA, GRC
Parker	Pete	Statistics/Reliability/DOE	NASA, LaRC
Snyder	Karma	Test & Systems Engineering	NASA, SSC
Thomas	Walt	Statistics/Reliability	NASA, GSFC
Behr	Vance	Parachute Systems	Sandia National Laboratories
Brown	Douglas	Statistics/Reliability/DOE	Booz Allen Hamilton
Herr	Michael	Parachute Systems	Naval Air Warfare Center, China Lake
McCullough	Jerry	Safety/Reliability	SAIC (retired Apollo)
Shidner	Jeremy	Modelling/Analysis	AMA, LaRC
Vitullo	Nick	Mechanical/Structures	ATK, LaRC
West	Bob	Parachute Systems	SAIC (retired Apollo)
Womack	Jim	Statistics/Reliability	Aerospace Corp
Won	Gary	Electrical/Avionics	ATK, GSFC

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<b>Interim Recommendation Outbriefed in April 2009</b>	Michael Kelly
	September 24, 2009


O-5: Review of Gen 1 test reports suggests that in 2007 and 2008 there was a lack of a systematic process in establishing the basis for and the conduct of testing. The Apollo Experience Report – Earth Landing System (ELS), NASA TN D-7437, (1973), illustrates the great extent of the testing that was necessary to demonstrate the overall reliability of the ELS system, to make it suitable for manned flight. It also illustrated the need for thorough systems integration and compatibility verification. Adopting a comprehensive systems approach to design, development and testing can deliver a robust, reliable system in a cost-efficient manner.

O-20: To ensure a robust and reliable design, the Apollo Program proved every part number and every assembly number by test or analysis to certify the system for man-rated flight.

F-6: There were no references to application of NASA SP-2007-6105, NASA Systems Engineering Handbook or NPR 7123.1A, NASA Systems Engineering Processes and Requirements in the material reviewed by the NESC team.

**R-5: Apply a *comprehensive systems approach* to the design development, analysis, and testing efforts. (O-5)**

- Address risks with priority given to those identified by the FTA to have the highest uncertainties (“risk balancing”).
- Include component-level verification tests to aid in tracking requirements compliance and risk acceptance/mitigation.
- Include planned means for verification and validation of simulation models.

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F-21: The CPAS Development Test Plan is derived from a project assessment of perceived or assumed risks. The reviewed plan:

- Does not link to all risks and concerns identified by FTA, FMEA, and PRA.
  - Some risks have been sequestered into a tab labeled 'off scope.'
- Lacks precise objectives and success metrics for each proposed test
  - Clear decision metrics are not included to establish when test objectives have been met.
- Includes configurations (in the "Test Matrix" tab) that illustrate a form of replication, but do not appear to be true replicated configurations.
  - The result could be a confounding of multiple factors without the ability to distinguish individual factor effects.
- Shows tests (in the "Test Matrix" tab) that are a fraction of all possible combinations summarizing the results of the Development Test Plan approach, rather than a strategic fraction used to define the development tests required.


O-25: Given resource limitations and the complexity and deeply integrated nature of CPAS, traditional, one-factor-at-a-time development testing may insufficiently assess performance, environmental factors, and interface interactions that can affect system reliability.

**R-31: Consider a statistics-based Design of Experiments (DOE) approach that features integrated, factorial test design, to more strategically and comprehensively plan development tests. (F-21, O-25, O-5, O-20)**

Such an approach would at a minimum include defining:

- **Precise, quantifiable test objectives**
- **Mathematical justification of test methodology and resources to support objectives and provide required confidence**



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F-22: The reviewed draft Verification and Validation Document (V&VD) indicated that CPAS verification tests will be derived principally from CPAS requirements. At the time of review, the V&VD did not contain details about the depth to which the verification plan will:

- Implement a methodology that rigorously traces verification tasks (analyses, testing, inspection and demonstrations) back to risks, component functions, and concepts of operations, in addition to requirements.
- Include precise objectives and success metrics (pass/fail criteria) for each proposed test.
- Consider the impact to verification of CPAS components that functionally interface with components of other subsystems.
- Include component-level and system-level special handling requirements as verification parameters.


F-23: Project personnel indicated that some (unspecified) development test data may be used for verification credit, although the draft V&VD indicates it will not. The V&VD indicates an intention to apply an "interactive process ... to evaluate and calibrate the analysis tools" during both development and verification testing.

- Development data from the limited number of configurations reflected in the test matrix may be insufficient for rigorous and comprehensive model or analysis validation and may have low inferential power.
- Development data generated using Engineering Development Unit test articles cannot be used for verification credit if the test articles are not sufficiently representative of flight units. Verification test articles must undergo the same quality control inspections as flight units.

O-26: To create a complete list of necessary verification tasks (analyses, tests, inspections, and demonstrations), a robust verification plan should be derived from a full inventory of component functions, functional requirements and identified risks. An incomplete component inventory may fail to identify failure modes that were not observed on heritage hardware or on previous tests on developmental hardware. An incomplete risk inventory may fail to identify relevant risks that can adversely affect crew safety and mission success.

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R-32: Create a comprehensive component-based verification plan as a parallel effort, to identify gaps and/or redundancies in the current system development test plan and the incipient verification plan. (F-6, F-21, F-22, F-23, O-26)

A detailed but incomplete component-based verification matrix that is consistent with this recommendation is provided as an example of the approach that would include:

- Systematic decomposition of the CPAS subsystem into components and their functions, including all functions that lead to factors that can influence CPAS performance.
- Identification of interfacing components (from other subsystems) that may influence CPAS performance, and their functions.
- Identification of environmental factors that can influence component performance.
- Identification of unique handling, processing, and inspection requirements.
- Inclusion of all risks and concerns identified by FTA, FMEA, and PRA.
- Derivation of verification parameters traceable to requirements, risks, and concept of operations.
- Derivation of an inclusive list of candidate verification tasks (analyses, tests, inspections and demonstrations) that rigorously trace back to risk analyses, component functional analyses, requirements, and concepts of operations.
- Cross checking with the existing development plan and the draft verification plan, to reveal potentially unidentified verification tasks that will be necessary to certify the system for man-rated flight.




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<h1 style="margin: 0;">Sample Component-Based Test Matrix</h1>	Michael Kelly
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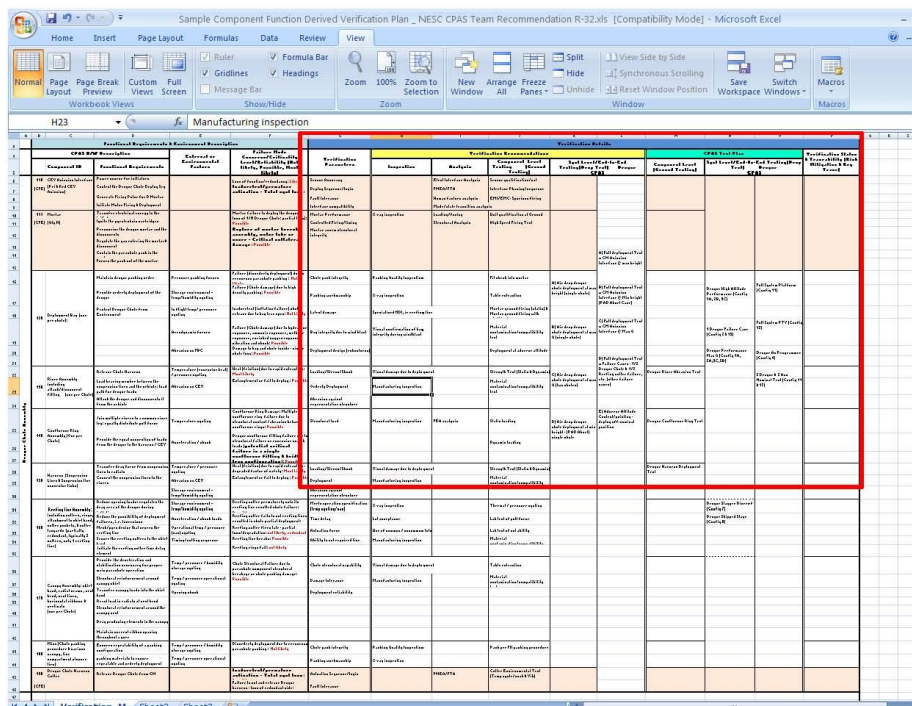
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<h1>Sample Component-Based Test Matrix</h1>	Michael Kelly
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Functional Requirements & Environment Description												Verifications
CPAS HW Description				Failure Mode Concerns/Criticality Level/Reliability (Not likely, Possible, Most likely)		Verification Parameters		Verification Recommendations				Verifications
Component ID	Functional Requirements	External or Environmental Factors						Inspection	Analysis	Component Level Testing (Ground Testing)	Syst Level Test	Or
110 CEV Avionics Interface (CFE) (Phi & Red CEV Avionics)	Power source for initiators Control the Drogue Chute Deploy Seq Generate Firing Pulse for D Mortar Initiate Motor Firing & Deployment			Loss of function/redundancy: Likely Inadvertent/premature activation - Total syst loss: Possible	Sensor Accuracy Deploy Sequence/Logic Fault tolerance Interface comp ability			Elect Interface Analysis FMEA/FTA Human factors analysis Model/state transition analysis	Sensor qualification/test Interface Phasing/sequence EM/EMC- Spurious firing Model/state transition analysis			
111 Mortar (CFE) (Qty N)	Transfer electrical energy to the igniter Ignite the pyrotechnic cartridges Pressurize the drogue mortar and the disconnect Regulate the gas entering the mortar's disconnect Contain the parachute pack in the mortar Forces the pack out of the mortar			Mortar failure to deploy the drogue (loss of MW Drogue Chute - partial loss) Possible Rupture of mortar breech assembly, motor tube or cover Critical collateral damage: Possible	Mortar Performance Controlled Firing/timing Mortar assem structural integrity		X-ray inspection	Load/gust testing Structural Analysis	Unit qualification at Ground High Speed Firing Test			
120 Deployment Bag (one per chute)	Maintain drogue packing order	Pressure packing forces		Failure (disorderly deployment) due to erroneous parachute packing: Not likely	Chute pack integrity		Packing Quality Inspection			Fit check into mortar		A) Air drop dro chute deployment max height (stg, chute)
	Provide orderly deployment of the drogue	Storage environment - temp/humidity cycling		Failure (Chute damage) due to high density packing: Possible	Packing workmanship		X-ray inspection			Table extraction		
	Protect Drogue Chute from Environment	In flight temp/ pressure cycling		Inadvertent (inflation failure) chute release due to bag tear open: Not Likely	Latent damage		Specialized NDI, ie reefing line			Mortar ground firing (static) & Mortar ground firing with -4-4-4		
		Aerodynamic forces		Failure (Chute damage) due to high ozone exposure, ammonia exposure, methane exposure, enriched oxygen exposure, vibration and shock: Possible Damage to bag and chute inside - single chute loss: Possible	Bag integrity due to wind blast		Visual confirmation of bag integrity during windblast			Material contamination/compatibility test		B) Air drop dro chute deployment max Q (single of
130 Riser Assembly including attach/disconnect fitting (one per Chute)	Release Chute Harness	Temperature (excessive heat) / pressure cycling		Heat (friction) due to rapid extraction: Most Likely Entanglement or fail to deploy: Possible	Loading/Stress/Shock		Visual damage due to deployment			Strength Test (Static & Dynamic)		C) Air drop dro chute deployment max Q (two chu
	Load bearing member between the suspension lines and the vehicle; load path for drogue loads	Abrasion on CEV			Orderly Deployment		Manufacturing inspection			Material contamination/compatibility test		
	Attach the drogue and disconnects it from the vehicle				Abrasion against representative structure							
140 Confluence Ring Assembly (One per Chute)	Join multiple risers to a common riser; leg- equally distribute pull force	Temperature cycling		Confluence Ring Damage: Multiple confluence ring failure due to structural contact/abrasion between confluence rings: Possible	Structural load		Manufacturing inspection	FEA analysis		Static loading		D) Air drop dro chute deployment height (P&Q) & single chute
	Provide the equal connection of loads from the drogue to the harness / CEV	Acceleration / shock		Drogue confluence fitting failure due to structural failure or excessive snatch loads (potential critical failure in a single confluence fitting & bridle legs configuration): Possible						Dynamic loading		
150 Harness (Suspension Lines & Suspension line	Transfer drag force from suspension lines to radials	Temperature / pressure cycling		Heat (friction) due to rapid extraction - degraded factor of safety: Most Likely Entanglement or fail to deploy: Possible	Loading/Stress/Shock		Visual damage due to deployment			Strength Test (Static & Dynamic)		
	Connect the suspension lines to the risers	Abrasion on CEV			Deployment		Manufacturing inspection			Material contamination/compatibility		

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<h1 style="margin: 0;">Sample Component-Based Test Matrix</h1>	Michael Kelly September 24, 2009
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Component ID	Component Name	Function	Verification Method	Test Results
101	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
102	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
103	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
104	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
105	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
106	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
107	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
108	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
109	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
110	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
111	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
112	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
113	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
114	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
115	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
116	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
117	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
118	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
119	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
120	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
121	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
122	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
123	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
124	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
125	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
126	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
127	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
128	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
129	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
130	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
131	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
132	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
133	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
134	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
135	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
136	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
137	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
138	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
139	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
140	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
141	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
142	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
143	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
144	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
145	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
146	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
147	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
148	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
149	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass
150	Parachute Assembly System	Deploy and Inflate	Visual Inspection	Pass

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<b>Sample Component-Based Test Matrix</b>	Michael Kelly
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Verification Parameters	Inspection	Analysis	Component Level Testing (Ground Testing)	Sgt Level/End-to-End Testing(Drop Test)	Drop CPAS	Component Level (Ground Testing)	Sgt Level/End-to-End Testing(Drop Test)	Drop CPAS	Verification Status & Traceability (Risk Mitigation & Req Trace)
Sensor Accuracy		Elect Interface Analysis	Sensor qualification/Interface Phasing/Sequence						
Deploy Sequence/Logic		FMEA/FTA	Interface Phasing/Sequence						
Fault tolerance		Human factors analysis	EMI/EMC- Spurious firing						
Interface compatibility		Model/state transition analysis							
Mortar Performance	X-ray inspection	Loading/fusing	Unit qualification at Ground						
Controlled Firing/Timing		Structural Analysis	High Speed Firing Test						
Mortar assem structural integrity									
Chute pack integrity	Packing Quality Inspection		Fit check into mortar	A) Air drop drogue chute deployment at max height (single chute)					
Packing workmanship	X-ray inspection		Table extraction						
Latent damage	Specialized NDI ie reefing line		Mortar ground firing (static) & Mortar ground firing with live fire						
Bag integrity due to wind blast	Visual confirmation of bag integrity during windblast		Material contamination/compatibility test	B) Full deployment Test w CM Autonics Interface @ Min height (PAD Abort Case)					
Deployment design (robustness)			Deployment at adverse attitude	C) Full deployment Test w CM Autonics Interface @ Max Q					
Loading/Stress/Shock	Visual damage due to deployment		Strength Test (Static & Dynamic)						
Orderly Deployment	Manufacturing inspection		Material contamination/compatibility test	D) Full deployment Test v Failure Cases - W2 Drogue Chute & W2 Reefing cutter failure, etc. (other failure cases)					
Abrasion against representative structure									
Structural load	Manufacturing inspection	FEA analysis	Static loading	E) Adverse Attitude Control/positioning - deploy off-nominal position					
			Dynamic loading						
Loading/Stress/Shock	Visual damage due to deployment		Strength Test (Static & Dynamic)						
Deployment	Manufacturing inspection		Material contamination/compatibility						

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# Introduction to Design of Experiments (DOE)


Pete Parker, LaRC

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*Statistical Design of Experiments*

*Parker (NASA LaRC) / NESC – CPAS Team Intro*




**Designed Experiment** - Purposeful control of the inputs (factors) in such a way as to deduce their relationships (if any) with the output (responses).

- Our use of “*experiment*” is not related to the technology readiness level

*“All experiments are designed experiments; the only question is whether well or poorly.”*

**Applicable to:**

- Characterization and Optimization of system performance
- Test and Evaluation for Verification and Validation

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### *Some Other Experimental Strategies*



#### **Intuition**

- can greatly benefit planning ► Never a sole strategy
- typically only "discover" what we already believe to be true

#### **One factor at a time (OFAT)**

- natural, systematic, and widely taught
- lacks ability to estimate interactions ► Assumes none

#### **Scenario, best guess, case by case**

- partitioning of easy versus hard experimental conditions
- results in an arbitrary fraction of all possible combinations


#### **Do what we did last time**

- could be good or bad
- low responsibility, high risk in repeating the same mistakes

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### *What is Design of Experiments (DOE)?*



#### **Design of Experiments is:**

- A structured experimentation and testing strategy
- A collection of tools to design, execute, and analyze experiments
- Not a replacement for good science and engineering

#### **Methodology that features:**

- Systems engineering perspective - emphasizes integration
- Efficiency with factorial experiments, information-intensive data
- 80+ year successful track-record


#### **Details of the Experimental Planning Process (Tutorial)**

- Coleman and Montgomery (1993) "A Systematic Approach to Planning for a Designed Industrial Experiment", Technometrics

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### *Fundamental Experiment Design Questions*



#### **Program and Project Definition**

- What are the precise objectives?
  - Are the objectives quantifiable, detectable, measurable?
  - What are we seeking to learn, new knowledge sought?
- How will we know when we have learned it?

#### **Technical Risk Management**

- How well do we need to know the answer (precision)?
  - What risk are we willing to accept if we are wrong about our conclusions?
  - What are the consequences if we are wrong?

#### **Planning and Execution**


- Do the methods support rigorous answers to the stated objectives and risk?
- Does the allocation of resources support the objectives and risk?
  - Are the resources justifiable and defensible?

*Questions apply recursively in the vertical direction through systems and subsystems and horizontally throughout project phases*

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### Some References




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## Appendix C.2. Supporting Frequently-Asked-Questions for Stakeholder Outbrief of Interim NESC Recommendations 2 (December 2009)

The team provided the material in this Appendix and discussed it with the Project in December 2009, to improve their understanding of material previously outbriefed during Stakeholder Outbrief 2 (September 2009).

### NESC CPAS team discussion at the Project MVP Tag-up

As an extension/reiteration of NESC CPAS assessment team recommendations approved by the NESC Review Board and communicated to the project in September 2009, the team suggests that all test planning (for verification or development) be started with a clear definition of the technical knowledge to be obtained about system performance, rather than starting with a pre-determined idea of what testing is acceptable within budget or schedule constraints.

Test matrices should be based on technical objectives, not perceived resource constraints.


We recognize the practical constraints that will be necessarily imposed on the magnitude of the test programs, and therefore a strategic, efficient testing approach should be developed. This approach should defend the resource requirements and quantitatively define the confidence (or risk) as a function of test resources.

To facilitate productive discussion, the team has prepared a list of six FAQs that address issues that have been discussed at recent CPAS MVP Tag-up meetings.

#### 1. “Why not drop it once under worst case conditions?”

The determination of worst-case conditions requires (1) an analytical determination of the settings of the controllable factors (e.g., altitude), (2) measurement of the uncontrollable factors (e.g., atmospheric, winds), and (3) traceability that the test article is representative of the actual flight unit. If those conditions are met, then the first drop provides a single statistical **sample** of the worst case with no information about **variability** in the responses (e.g., descent rate) observed. Without multiple samples a data-driven estimate of variability cannot be obtained, and therefore a data-driven statement about **confidence** (inversely proportional to variability) in the results is not possible.

With multiple drops, we obtain **replicates** of the factor settings (controllable and uncontrollable) with multiple test articles to estimate **experimental variability**, which is the variability in the response (e.g., descent rate) when the settings are identical (identical within the experimental system’s ability to control and measure). In contrast, **repeated** measurements are obtained from a single setting of the factors on a single test article.

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Repeats, or **sub-samples**, provide the ability to estimate measurement noise, which is a component of experimental variability (usually a very small component).

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2. “Why not partition a single drop to obtain multiple samples?”

Partitioning a single drop test provides **sub-samples**, not replicates, and therefore the variability of the test article and factor settings will most likely be underestimated resulting in an inflated confidence level. Underestimating the variability can result in an inferential error (i.e., conclusion drawn from data) in which we declare that the requirement has been met when in fact it is not.

Employing partitioning a single drop as a data analysis method can provide other valuable information, but it is not a replacement for experimental replication.

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3: “Does the CPAS need to perform across a range of values or only at an extreme value?”

Several requirements, such as I.CPAS.CM.133, listed in JSC-63497 refer only to extreme values, i.e., max and min values along a range. Listing only the extreme values assumes that values falling within the extremes are not dangerous. It also assumes that interactions between variables are not consequential.


Failure to test non-extremes could result in an increase in the probability of mission loss. Further, testing only extreme values is akin to one-factor-at-a-time testing (OFAT). OFAT is an inefficient method for determining the effect of a factor on the system. Performing OFAT correctly requires an exorbitant amount of testing resources and fails to account for the interactions of one factor with another. Factorial experiments (DOE) are the only way to detect interactions.

For example, the CPAS may perform under an extreme condition for each of two variables. However, the CPAS may fail when two variables are jointly set at some values below their respective extremes. Given that failure can occur at any value within a range of values; all requirements should specify a range of values that the CPAS must perform within.

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4: “Why include probability measures for each of the requirements?”

JSC-63497 does not specify a probability threshold for compliance with the requirements listed. This leaves the contractor to interpret how well and how often the CPAS must meet a given requirement.

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5: “Why not center the MVP testing strategy around verification activities?”

The current MVP testing strategy centers around verification activities. As a result, the number of verification activities and types of verification activities are determining testing resources. Focus on verification activities as a generator of test runs neglects the actual causes of failure for CPAS. Verification activities provide a context and scenario for testing the CPAS but are not necessarily linked to the factors that affect CPAS performance.


MVP testing strategy should focus on the factors that affect the ability of the CPAS to perform against its requirements. Verification activities should be a secondary concern for providing a context in which the performance factors can be varied through their required sample space. Care should be taken to minimize the number of verification activities while maximizing the number of factors stressed in each verification activity.

6: “Can the MVP testing strategy meet all of the CPAS requirements within budget?”

Documentation for the MVP testing strategy does not have a planning matrix listed. Without a planning matrix it is unclear as to how verification testing will meet all of the requirements within their resources and within their schedule.

The planning matrix should list, at a minimum: the requirement, CPAS function under test, and number of runs. After the planning matrix is built, a DOE matrix could easily follow from this construct. An example matrix adopted from “A Systematic Approach to Planning for a Designed Industrial Experiment” by Montgomery & Coleman is below.

Requirement	Response Variable	CPAS Function	Hold-constant factors	Nuisance factors	Control factors	Number of runs
[I.CPAS.CM.13 4]	Probability of successful release	forward bay cover (FBC) release	Altitude	Temp Wind Speed	CM total angle of attack	XXX

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**Appendix D.1. Stakeholder Outbrief of Interim NESC  
Recommendations 3 (April 2010)**

**Stakeholder Outbrief  
of Interim NESC Recommendations**

*Rev 01, 04/12/10*


**Project Assessment between  
September 2009 and March 2010**

**Crew Exploration Vehicle (CEV)  
Parachute Assembly System (CPAS)  
Independent Reliability Assessment  
(TI-08-00487)**

**April 12, 2010**

**Mr. Michael Kelly**

**NESC Principal Engineers Office**

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## **November 2008—Stakeholder Request**


*“Review the reliability analysis of the CPAS in the context of the existing design and planned development program and make recommendations for improving either (the design or the planned development program), if appropriate. Identify design and/or process improvement opportunities to increase the overall reliability of the CPAS as well as to ensure the success of the integrated (CPAS) system. Of particular interest is the planned development test program due to its value in uncovering design flaws contrasted with the cost and resources required. Striking the proper balance between reliability enhancing tests and total project cost and schedule is important for the success of the Program.” - Steve Altemus*

## **Notes to Stakeholder**

*The 23 Interim NESC Recommendations herein (R-33 through R-55) are directed towards the CPAS project, unless otherwise indicated. These are interim recommendations, consistent with the scope of the request. Those considered top-priority are underlined.*

*All previous findings, observations, and interim NESC Recommendations are included in backup material.*

*A final report will be delivered in June, 2010. Bulleted information seen throughout this document is provided for stakeholder clarity, and will ultimately appear within narrative in the final report.*

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## I. DESIGN-DEVELOPMENT-RELATED INTERIM NESC RECOMMENDATIONS

F-24: The project choice of segmenting the Forward Bay Cover (FBC) into six airbag-jettisoned panels appears to have been made without detailed consideration of certain key aspects.

- Fail-safe requirements
- Airbag load reaction on the main packs
- Panel separation line features
- Volumetric requirements
- Panel release velocity uncertainties
- The effect of residuals from mild detonating cord (MDC) detonation on susceptible components in the compartment.

F-25: FBC panel post-jettison trajectory analyses did not include important effects.

- Variation in airbag thrust vector direction
- Air flow around the CM at off-nominal CM attitudes
- Panel tumbling and rolling
- The range of potential panel ballistic coefficients resulting from a variety of airbag inflated shapes or shape differences of the panels that cover the drogue mortar bays

F-26: An analysis model of undemonstrated validity was used with a set of simplistic assumptions to provide translational trajectory predictions of jettisoned FBC panels to support design trade decisions and conclusions:


- The change from a monolithic FBC to a six-panel, segmented FBC
- The preference of six panels versus fewer, larger panels
- The conclusion that the panels' terminal velocity would be ~92 ft/sec
- The conclusion that the panels' required jettison velocity was 100 ft/sec

F-27: FBC panel trajectory analyses were conducted for nominal reentry but not for aborts.

F-28: No multi-body trajectory analyses were conducted of *dispersed relative* trajectories of FBC panels, drogue chutes, pilot chutes, main chutes or other liberated components.

F-29: The risk and consequences of *near-field contact* between FBC panels and parachutes have not been rigorously assessed.

- During descent after reentry, a short interval is planned between FBC panels' jettison and drogue mortars' firing to reduce the risk of CM angular-rate buildup, but this may introduce the risk of a drogue parachute being fired into and contacting a jettisoned panel.
- Following launch abort system (LAS) handoff after an abort, a short interval is planned between FBC panels' jettison and pilot mortars' firing to reduce the risk of CM angular-rate buildup. However, this may introduce a risk of a pilot parachute being fired into and contacting a jettisoned panel.

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F-30: The risk and consequence of *far-field contact* of FBC panels with parachutes have not been rigorously assessed.

- FBC panel jettison airbags must provide positive separation of all six panels from the CM, drive them outside the deployment radius of any of the parachutes, and set them on flight paths that will not intercept the CM on its parachutes.
- Jettison may occur in a complex air stream that is highly dependent upon capsule orientation relative to the wind vector.
- The probability of any one jettisoned panel (out of a set of six) contacting a parachute is greater than the probability of a single monolithic cover contacting a parachute.

O-27: Analysis tools used by the military to assess aircraft survivability in hostile environments may be helpful for analysis of far-field contact.


- Reference: *The Fundamentals of Aircraft Combat Survivability Analysis and Design, 2nd Edition*, Robert E. Ball, Naval Postgraduate School, American Institute of Aeronautics and Astronautics (AIAA) Education Series C 2003, 2nd Edition, 889 pages, mixed media, ISBN-10: 1-56347-582-0, ISBN-13: 978-1-56347-582-5.
- <http://aircraft-survivability.com/>

**R-33: Assess the risks (likelihood/consequences) of *near-field* re-contact from firing a drogue or pilot parachute into a jettisoned FBC panel, and of *far-field* re-contact of a panel with any drogue, pilot, or main parachute component, by conducting a comprehensive development test and analysis program. (F-24, F-25, F-26, F-27, F-28, F-29, F-30, O-27)**

F-31: Project analyses of the risks and consequences of unsuccessful panel jettison due to either MDC fail or airbag fail were not shown.

- A failure of one of the panels on a drogue mortar sector to jettison may result in the improper deployment, or failure to deploy, of one drogue parachute *and* the improper deployment of, or failure to deploy, of one pilot parachute (and consequently one main parachute).
- A failure of the panel to jettison from the sector with the CM Uprighting System (CMUS) tanks may result in the improper deployment, or failure to deploy, of one pilot parachute (and consequently one main parachute).
- A failure of one panel to jettison from one of three sectors with main parachutes may result in the improper deployment, or failure to deploy, of one main parachute; if in this event the pilot riser physically releases the stuck panel at line stretch, this would pose increased risk of main parachute damage.



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- Retained FBC panels are apparently not designed to break away or fail by drogue or pilot parachute deployment.

O-28: Aircraft ejection-seat escape systems that rely on MDC to rupture a cockpit canopy often include physical strikers mounted on the upper-most position of the seat as a fail-safe feature.

**R-34: Assess the risks (likelihood/consequences) of any FBC panel failing to separate from the CM by conducting a comprehensive development test and analysis program. (F-31, O-28)**

F-32: Computer algorithms for panel jettison and subsequent firing of mortars are poorly defined.


- The timing sequence and control of FBC panel deployment should be considered a risk mitigation design parameter.
- Algorithms must be sufficiently defined to enable project engineers to understand the event sequence.

O-29: Initial trajectories and motions of FBC panels will be sensitive to variations that will be inherent in several closely sequenced initial events.

- MDC detonation events
- Initiation of airbag inflation
- Rate of airbag inflation
- Push-off force

**R-35: Consider implementing an *error margin budget* that is derived by Monte Carlo simulation, in the FBC deployment design and analysis effort. (F-32, O-29)**

- An FBC deployment error margin budget could include (with example values):
  - Timing mismatch between FBC separation and airbag inflation (ultimately effective  $\Delta v$  from airbags) (e.g.,  $0 + 0.05$  sec 3-sigma, Gaussian distribution).
  - Airbag inflation rate and panel stability (e.g.,  $5 \pm 0.10$  m<sup>3</sup>/sec 3-sigma, Gaussian distribution).
  - Time allowed in free-fall between FBC jettison and chute deploy (e.g.,  $1 \pm 0.1$  sec 3-sigma, Gaussian distribution).
  - Atmospheric density (e.g.,  $\pm 0.001$  kg/m<sup>3</sup> 3-sigma, Gaussian distribution).
  - CM attitude at FBC separation and chute deploy (e.g.,  $180 \pm 50$  deg 3-sigma, Gaussian distribution).

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- An error budget could be interrogated:
  - Do the budgeted dispersions (uncertainties) meet the design requirement?
  - Can the design requirement (e.g., acceptable range from FBC at parachute deploy) be changed to accommodate the budgeted dispersions (uncertainties)?
- Mars Science Laboratory (MSL) Entry, Descent, and Landing (EDL) designers employed an error margin budget to various operational phases, as described in: *Mars Science Laboratory Entry, Descent, and Landing Triggers*, Kipp, D., et al. (2006), Institute of Electrical and Electronics Engineers Aerospace Conference (IEEEAC) paper #1445, Version 2, Updated 2006:12:27.

**R-36: Validate the aerodynamic trajectory analysis by conducting appropriate wind tunnel, ground, and/or flight tests. (F-26, F-28)**

- Consider subjecting a family of test panels that envelopes a best-guess range of panel dimensions, to vertical wind tunnel testing or free fall from an aircraft; investigate panels with variously deflated airbags in this same manner.
- Characterize the nature of terminal descent of the six panels (stable, metastable, unstable).
- Verify the assumptions/analysis of flight stability and ballistic coefficients.
- Conduct full 3D multi-body Monte Carlo trajectory analyses using dispersed aerodynamic parameters that encompass the FBC panel testing campaign's derived uncertainty.

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F-33: The CPAS main parachute stowage bay geometry is more restrictive of unhindered extraction than was the heritage Apollo Earth landing system (ELS).

- The CPAS forward bay gusset geometry provides a 60-degree sweep of unhindered extraction, compared to 90 degrees for the ELS.
- The ramp on the upper back side of the three CPAS main-deployment bags will hinder upward extraction above the angle of the ramp.

F-34: The project decision to classify the risk of deployment bag contact with forward bay features during extraction as “off scope” in the development test matrix was not based on test data.

- Consequences could include deployment bag extraction failure or extraction delay and damage to packed main parachute components.

**R-37: Assess the risks (likelihood/consequences) arising from main parachute pack assembly contact with CM features during extraction by performing analysis and**

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**conducting a comprehensive development test and analysis program using a representative forward bay mock-up. (F-33, F-34)**

F-35: Some of the main parachute retention options being considered expose the daisy-chain locking loops and their associated lanyards to risks of abrasion and heat damage.

F-36: The latest reviewed main parachute retention system (March 2010) exhibits rigging complexity that introduces new risks of failed or delayed extraction of a main parachute pack.

- No mechanism was shown for the left/right pilot riser halves to impart forces to unzip their associated daisy-chain loops; risers would require one-for-one integration with each locking loop to pull each loop through its associated grommet. This concept has no apparent precedent.

O-30: Parachute extraction, deployment, and inflation have historically required testing because these events are difficult to analyze.

**R-38: Conduct development ground testing to assess retention system options *before* submitting the preliminary design to aerial drop tests. (F-35, F-36, O-30)**

- Ground tests could include a series of static and dynamic strip tests at various pull angles on a representative forward bay mock-up.

F-37: The system of corsets and beackets on the outer deployment bag surface of the current iteration of the main parachute retention may insufficiently support the convex-curved upper-outer edge of the main parachute pack.


O-31: Inertial forces may shift a pack in its retention system, altering its top and outer surfaces and particularly affecting its curved upper-outer edge. Such movement or distortion could allow contact of the deployment bag with the FBC inner mold line (IML), consequently damaging parachute components.

O-32: The lock/loop release concept on the current iteration of the main parachute retention system appears unnecessarily complex in that it requires pilot risers to un-loop each link during deployment.

- Diverges from the Apollo model by restraining the packs along their side edges instead of along their top and bottom edges.

**R-39: Assess design options and risks (likelihood/consequences) of failure of the main parachute deployment bag corset-and-becket restraints by conducting development tests of a variety of restraint schemes under vibration and shock. (F-37, O-31, O-32)**

- Pay particular attention to risks along the convex-curved upper-outer edge of the main parachute deployment bags and consider incorporation of stiffening material.

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O-33: Movement internal to a main parachute pack can result in premature reefing line cutter initiation, as may have contributed proximally to the Ares 1-X test parachute performance anomaly.

**R-40: Ensure the adequacy of the cutter actuation system design load safety margins to preclude premature reefing line cutter initiation during packing, transport, or flight, while ensuring actuation during the dynamic conditions of deployment. (O-33)**

- Consider the cutter actuator, initiation lanyard, attachment loops, safing ties, and stowage procedure.

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F-38: The torque limiter design feature for limiting roll torque has no precedent and can induce failure modes into CPAS that will require extensive deployment testing.

O-34: The requirement to use the roll control system (RCS) for touchdown roll orientation control appears to be a remnant from the time when the CM was being designed to withstand land landings. The RCS is being relied upon to limit structural loads during water landings. The use of the RCS after FBC jettison may adversely affect the reliability of CPAS, by introducing risks of burning or oxidizing damage to textile materials, especially at high CM angular rates and attitudes.

O-35: Integrated risks and consequences associated with the RCS do not appear to have been comprehensively assessed.

**R-41: The Orion Project should consider chartering an Integrated Design Assessment Team (IDAT) to conduct a comprehensive assessment of CM roll control effectiveness at limiting landing loads on the vehicle. Include representatives from all CM subsystems that interface with or are dependent on the RCS function, including CPAS. (F-38, O-34, O-35)**

- The assessment scope could include:
  - The overall feasibility and ramifications of using the RCS for touchdown roll control
  - Assessment of the risks (likelihood/consequence) versus benefits to CPAS and other subsystems
  - The impact of prohibiting the use of the RCS once the FBC panels are deployed
  - The impact of a requirement to not dump RCS fuel in any direction where heat, fuel, or oxidizer can reach any part of the parachute system
  - Inclusion of a deployable metallic torque limiter in the CPAS system

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- Design of the CM structure for water impact at worst-case combinations of water-surface conditions and vehicle-landing attitudes
- The risks of landing with fuel in the RCS tanks
- The effects of parachute oscillation
- The ability to sense CM drift direction
- The ability to sense water-surface conditions beneath the CM prior to landing
- The methods to determine which heading to take to impact a dynamically changing wave slope just right
- RCS command sequencing
- The extent and complexity of an adequate development and certification plan for the RCS

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O-36: The 2009 IDAT outer mold line (OML) change provided increased forward-bay volume for packaging CPAS components, but growth during forward development should be expected. Main parachutes may grow in size to reduce landing loads. CM weight increases may drive other increases in volume requirements. Main parachute retention locking loops, flaps, reinforcing bars, grommets, corsets, and beackets do not appear to be included in volume accounts for forward bay sectors where the main parachutes are stowed. The immaturity of the routing scheme for the lines that will secure the inflated CMUS bags may adversely impact available volume for CPAS.

***Reiteration of NESC Interim Recommendation outbriefed in April 2009:***

**R-3: Evaluate the use of a volume budget for the forward bay to manage main parachute pack volume growth before and after PDR. (F-1, F-2, O-3, O-36)**

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## II. PRA-RELATED INTERIM NESC RECOMMENDATIONS

F-39: Failure estimates in the CPAS Probabilistic Risk Assessment (PRA) have evolved with the architecture but have never completely or accurately reflected CPAS risks.

- The driving failure estimate in December 2008 was based on inapplicable data from solid rocket booster (SRB) experience.
- Mid-2009 failure estimates were based on engineering judgment.
- Subsequent failure estimates (and uncertainty estimates) were based on the results of a dubious expert elicitation exercise.
- CPAS PRA input values at all stages have been used for computations of CPAS contributions to Orion's risk of loss of crew (LOC).

F-40: Between April 2009 and March 2010, few ground tests were conducted to generate data for PRA estimates, as previously recommended.

F-41: Risk-informed design decisions have been made based on PRA models that have not been verified and validated.

O-37: Early PRA failure estimates are predicted, not demonstrated, but they ultimately require some verification of driving assumptions by analysis that has been anchored by some limited testing.

**R-42: Include the source (e.g., historical, test, analysis, expert elicitation) and a clear explanation of the veracity of all CPAS PRA estimates when provided to the Orion Project for use in overall LOC summaries. (F-39, F-40, F-41, O-37)**

**R-43: The Orion Project should establish guidelines for generating PRA failure estimates for use on all subsystems, whether contractor-furnished equipment (CFE) or government-furnished equipment (GFE). (F-39, F-40, F-41, O-37)**

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F-42: The methodology employed in the CPAS expert elicitation exercise assumed that the events were all independent, but some were dependent.


F-43: The methodology employed in the CPAS expert elicitation exercise assumed that the events were comparable, but experts were asked to compare input events at disparate levels.

**R-44: Consider applying the Analytical Hierarchy Process (AHP) or a similar decision-ranking technique, to event sets that are truly independent and comparable, in any future expert elicitation exercise. (F-42, F-43)**

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F-44: The response data from the expert elicitation exercise exhibit large variability.

- The large variability between experts:
  - Suggests lack of agreement among the experts

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- Indicates problems with the elicitation protocol, including the collection of events and their precise definition, and/or the analysis approach
- Impugns the validity and applicability of the results
- Makes the use of the results difficult to defend

F-45: Deleting PRA failure events associated with the architecture change renders the current expert ranking inapplicable.

- Experts used in the elicitation exercise considered the “Harnesses Drogues and Monolithic FBC” architecture prior to the change to the “Modified Apollo” architecture.

O-38: A cache of heritage Apollo ELS test and reliability reports has been located and will soon be retrieved by the project.

**R-45: Discontinue using results from the existing expert elicitation exercise for CPAS design decisions or for PRA/LOC estimates until failure estimates are revised to reflect the current architecture and the cause of large variability from that process can be determined. (F-44, F-45)**


**R-46: Utilize applicable data from the geometrically similar Apollo Program ELS to generate estimates for applicable failure estimates or conduct tests and analyses to generate new PRA data. (F-44, F-45, O-38)**

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O-39: CPAS may gain insight into the “Modified Apollo” architecture reliability by conducting a reliability growth analysis of the Apollo ELS test data.

- A reliability growth analysis/trending analysis of the original Apollo ELS would provide a baseline for present-day development.
- Reliability growth methods indicate progress toward system reliability goals during a development program and provide management with a means to detect adverse (and positive) trends and proactively effect programmatic adjustments.
- A *programmatic* reliability growth analysis would use calendar time and programmatic failures (e.g., failure to meet schedule, requirements, or test objectives).
- As CPAS components are primarily ‘one-shot’ devices, a growth analysis to derive failure or reliability data will require a different approach (e.g., plotting sequential test failures versus tests run for both component- and system-level tests).



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- An example reliability growth application for a NASA space instrument is available in the backup material.

**R-47: Consider performing a *reliability growth analysis* using Apollo ELS test data. (O-39)**

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O-40: Based on similarity, the Modified Apollo architecture will have a comparable number of risks driving its development program as did the Apollo Block I ELS.

- Block I (early development) aerial drop tests accounted for 76 percent of all ELS aerial drop tests conducted.
- Approximately 80 percent of ELS development tests were driven by the abort conditions.

F-46: The Project has conducted few system-development tests supporting the various design concepts it has vetted.

F-47: Ground and air-drop development testing should be better integrated into the overall design effort.

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F-48: At IDR3, development tests were discussed for use for qualification credit. *F-23*

### **III. ANALYSES-AND-TESTING-RELATED INTERIM NESC RECOMMENDATIONS**

F-48: At IDR3, development tests were discussed for use for qualification credit. *F-23*


**R-48: Apply development test results for qualification credit only if the configuration unambiguously represents the qualification configuration and this representation has been rigorously documented. (F-48)**

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F-49: The CPAS development test schedule is ambitious, with tests planned every 2–3 months starting late in 2010.

O-41: Resource (cost and schedule) constraints appear to drive testing activities and may have adversely impacted the sufficiency of tests conducted to date. The test team appears to be one-deep in some skills, and may not be capable of meeting the test rate, or flexibly managing the impact of test failures (even minor failures).

**R-49: Consider reorganizing the development test conduct team to allow multiple test subteams to conduct parallel activities. (F-49, F-50)**

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F-50: A draft DOE test plan was created by a project statistician after NESC Interim Recommendation R-31 was outbriefed, but the plan was not incorporated into the development test planning process.

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O-42: Insufficient photographic and riser loads test instrumentation hindered investigation of parachute failures that occurred during the Ares 1-X flight test.

**R-50: Include photographic and test instrumentation on all aerial drop tests, sufficient not only to meet the requirements for nominal performance, but also to assist determining foreseeable failure causes. (O-42)**

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F-51: Statistical results from parametric analyses of un-shown validity have been used to inform design decisions.

**R-51: Recognize and convey to decision makers the maturity of analytical models and the resulting uncertainties prior to their use in supporting design decisions. (F-26, F-51)**

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F-52: DCLDYN does not have the capability to model clustered canopies as independent bodies.


F-53: The fraction of cluster load-sharing shown at IDR3 was not correct for the system presented.

- The load share fraction used was based on one Apollo mains test point, and had been chosen by the Hardware Integrated Product Team (IPT) (as detailed in the IDR3 backup charts).

O-43: The fraction of load sharing has a significant and important effect on the structural analysis of the parachute and the hardware connections to the CM and should be tracked during development. Cluster performance and load-sharing data over the range of deployment conditions is needed early in the design process.

O-44: Various simulation models are available for modeling parachute clusters.

- The NASA LAS team conducts multi-body MC analysis using four different simulation tools: Decelerator System Simulation (DSS), Program to Optimize Simulated Trajectories (POST), Advanced NASA Technology Architecture for Exploration Studies (ANTARES), and OSIRIS.
- DSS uses three degrees of freedom (3DOF) multi-body parachutes that are independent of the capsule and other parachutes in the cluster. The three-chute DSS cluster modeled during IDAT remains unvalidated.

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- POST uses 6DOF multi-body parachutes that are independent of the capsule and other parachutes in the cluster. The POST simulation multi-body model has been partially validated per NASA TM-2002-211634. The 6DOF aerodynamics is not known for CPAS, and therefore POST uses scaled SRB parachute aerodynamic data.
- ANTARES and OSIRIS share common simulation frameworks and the same multi-body model.

**R-52: Develop a drag model to accommodate multiple bodies in a shared environment that represents a chute cluster such that MC runs can assess variations in inflation times and opening loads between chutes. (F-52, F-53, O-43, O-44)**

#### **IV. REQUIREMENTS-AND-VERIFICATION-RELATED INTERIM NESC RECOMMENDATIONS**

F-54: The Project Technical Requirements Specification (PTRS) does not define pass/fail criteria quantitatively, nor require an explicit statement of test suitability, assumptions, or statistical confidence in the test and/or simulation data and analysis.

**R-53: Revise the PTRS to unequivocally ensure verifiable pass/fail metrics that require a quantitative and defensible development testing approach and analysis. (F-54)**


- State what needs to be known, how well it needs to be known, and how it will become known that it has been learned.
- Reference EA-07-005, *Verification of Probabilistic Engineering Requirements Prepared for Constellation Chief Engineers Forum by Verification of Probabilistic Requirements Team*, for format of the requirements.
- For example: “The CPAS will ensure with XX percent statistical power at an effect size of X.X m/s that the CM will not exceed 10.7 m/s” or “The CPAS will ensure with 90 percent confidence that the 0.3-percentile (3 sigma) of the strength of component A exceeds X ft-lbs.”

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F-55: The draft Master Verification Plan (MVP) appears to emphasize aerial drop tests over ground tests.

- Integration of verification activities is forward work.

**R-54: Implement a comprehensive verification process that is linked to the requirements revised per R-53. (F-55)**

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- Emphasize a bottom-up test and verification approach over system-level drop tests. Verification activities should be performed at the lowest level possible and built up to mitigate the unnecessary risk and control all external effects. For example, the riser assembly mechanical strength qualification can be done as a component level test versus during an all-up system drop test.
- Develop a test matrix based on the most probable worst-case flight conditions and environmental factors (on a bad day/worst case), clearly state those conditions in reporting the results, and restrict acceptable flight conditions as limited to those that have been tested. The project seeks to “test as you fly and fly as you test” but it is often impractical to develop a test matrix that will encompass all external environmental variables and interactions between its subassembly components, especially for a system as complex as CPAS.
- Use statistical DOEs in all testing levels (component to flight) to optimally use resources for requirement verification (PTRS revised per R-54).

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F-56: The CPAS Project’s use of statistical assumptions, methodology, and analyses has not been consistently rigorous or defensible.


**R-55: Integrate statistical expertise in the decision-making process throughout the design, development, and testing processes. (F-50, F-56)**

## V. LESSONS LEARNED FOR FUTURE PROGRAMS AND PROJECTS

O-45: The IDAT work and the Lockheed Forward Bay Technical Interchange Meeting (TIM) addressed many CPAS integration issues. LRS Forward Integration Team (FIT) involvement in CPAS integration activity will benefit the project. However, complex reporting lines, roles, and responsibilities that arise from CPAS being GFE may pose risks to designing a well-integrated and reliable subsystem.

O-46: During Apollo, the ELS organization was responsible for the total upper deck Interface Control Document (ICD), allowing them to control anything that could interfere with parachute function.

**LL-2: Developers of parachute architectures for recovery of human-rated space vehicles should assign control of the parachute compartment ICD to the parachute system development team. (O-45, O-46)**

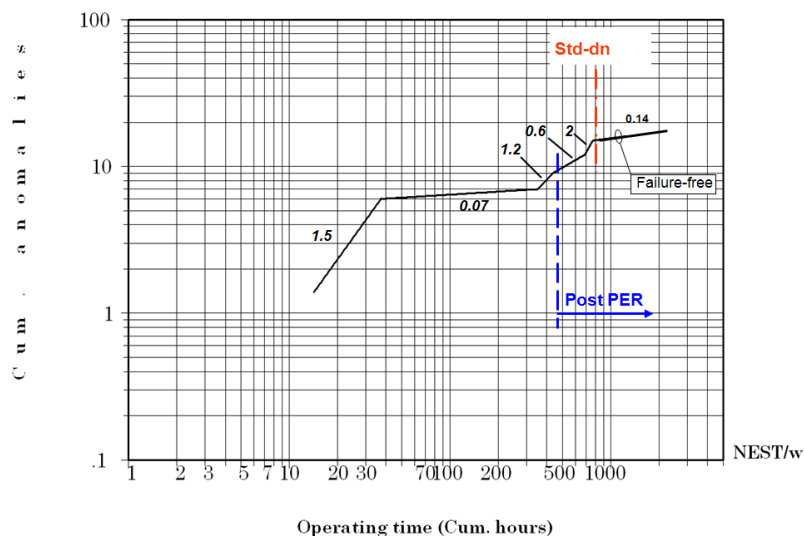
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## Appendix D.2. Supporting Example of Reliability Growth Trending

The following backup material was provided to the Project with the Stakeholder Outbrief of Interim NESC Recommendations 3.


### BACKUP ITEM: EXAMPLE SUPPORTING INTERIM R-47

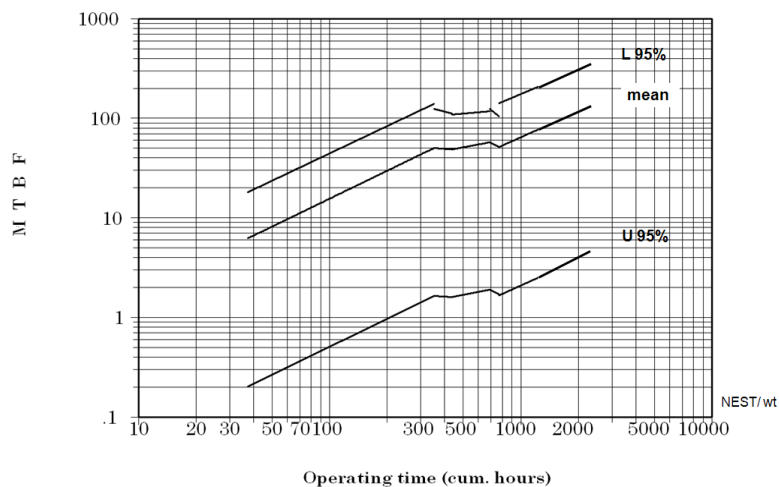
An example application for a NASA space instrument is provided that used reliability growth trending during development. The following graph is a Crow-AMSAA plot (so-named for Dr. Larry Crow and the U.S. Army Materiel Systems Analysis Activity), aka a CA plot, or a reliability growth plot, of this instrument during integration and test. The inflections (slope changes) are points at which failures occurred, fixes implemented, and testing continued. After several failures occurred “post-PER,” the program stood down, revised their processes, and implemented other fix measures. The slope change from 2 (degradation, or “negative” reliability growth) to 0.14 (excellent reliability growth) indicated that the stand-down and changes implemented were effective in reversing the prior adverse trend.




**Reliability growth of a space Instrument undergoing T-A-F (test-analyse-fix).**  
*Italic numbers adjacent lines are fit slopes, indicating growth (<1) or degradation (>1).*  
 Instrument has operated last ~ 1400 h failure free since a stand-down.

The following graph is a mean-time-between-failures plot derived from the CA plot. It shows reliability and uncertainty trends, including confidence intervals. Similar plots for failure rate are also available.

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**Mean-time-between failures derived from the reliability growth plot.**  
Confidence intervals are shown (90% total, or upper and lower 95%), and are available also for derived failure rate.

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## Appendix D.3. Supporting Example of Potential Problems with OFAT Testing

The following backup material was provided to the Project with the Stakeholder Outbrief of Interim NESC Recommendations 3.

### BACKUP ITEM: EXAMPLE OF PROBLEMS THAT CAN ARISE WITH ONE-FACTOR-AT-A-TIME (OFAT) TESTING

Consider the following experiment where the engineer is interested in determining the values of factors  $x$  and  $y$  that produce the highest stress. Suppose we fix factor  $y$  at 155 (the nominal value) and perform four tests at different levels of factor  $x$  – say, .5, 1.0, 1.5, and 2.0. The results are shown in Figure 1. This figure indicates that the maximum stress is achieved when factor  $x$  is about 1.3.

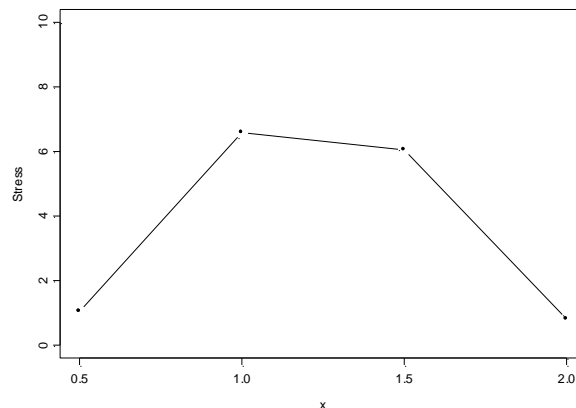



Figure 1: Stress versus factor  $x$  with factor  $y$  constant at 155

To determine the effect of factor  $y$  fix factor  $x$  at 1.3 (the apparent optimal value) and perform six tests at different levels of factor  $y$  – say, 140, 150, 160, 170, 180, and 190. The results of these tests are plotted in Figure 2. The maximum stress occurs at about 165. Therefore we would conclude that the worst case stress occurs at  $x = 1.3$  and  $y = 165$  resulting in a stress of about 9.



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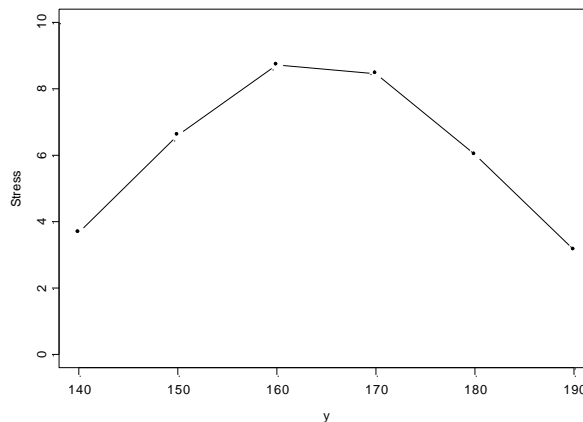


Figure 2: Stress versus factor y with factor x constant at 1.3

Figure 3 displays the contour plot of stress as a function of x and y with the one-at-a-time tests shown on the contours. We now see that the one-at-a-time testing has failed here, as the true worst case is over 50% higher (greater than 14) and occurs when  $x = .7$  and  $y = 185$ .

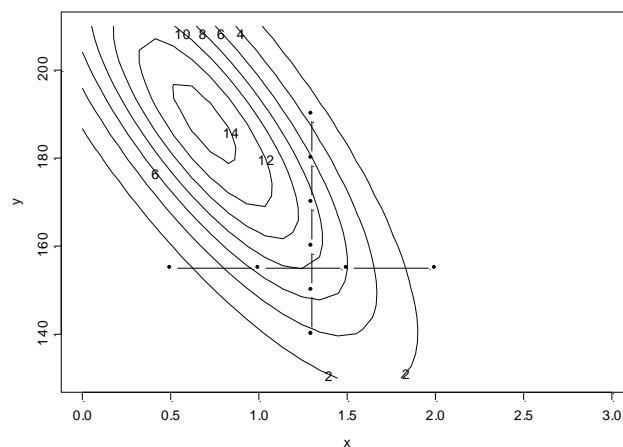


Figure 3: Stress experiment using one-factor-at-a-time method

The one-at-a-time testing has failed here because it failed to detect the interaction between the two factors. Factorial experiments (DOE) are the only way to detect interactions. In addition the one-at-a-time method is inefficient; it requires more tests than a factorial, and there is no assurance that it will produce the correct results.

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